Lecture 17
More Particle Physics
News

- Exam 2: Wednesday March 31 (next week!)
  - Hoyt at 2-3.15 pm, instead of class
  - Bring a **calculator**
  - I will provide a formula sheet
  - Material: lectures 8 – 15 (up to nuclear physics, life of a star), recitations 5-7

- I'll be available in my office Monday-Wednesday
  - Come see me if you have questions!

- No recitations or problems next week
Last layer in the onion? $10^{-18}$ m

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
Quantum field theory

Forces are “carried” or “mediated” by particles: exchange force

Electromagnetic
Weak
Strong

**BOSONS**

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^-_-$</td>
<td>80.39</td>
<td>-1</td>
</tr>
<tr>
<td>$W^+_+$</td>
<td>80.39</td>
<td>+1</td>
</tr>
<tr>
<td>$Z^0$ Z boson</td>
<td>91.188</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strong (color)</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g$ gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
# Matter and forces

## Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton</td>
<td>$W^+$, $W^-$, $Z^0$</td>
<td>$\gamma$</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength at</td>
<td>$10^{-18}$ m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^{-17}$ m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^{-41}$</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>1</td>
<td>60</td>
</tr>
</tbody>
</table>

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## FERMIONS

**Leptons**

- **Flavor**: $\nu_L$, lightest neutrino
- **Mass**: $(0-0.13) \times 10^{-9}$ GeV/c$^2$
- **Electric charge**: 0

**Leptons**

- **Flavor**: $e$, electron
- **Mass**: 0.000511 GeV/c$^2$
- **Electric charge**: -1

**Leptons**

- **Flavor**: $\nu_M$, middle neutrino
- **Mass**: $(0.009-0.13) \times 10^{-9}$ GeV/c$^2$
- **Electric charge**: 0

**Leptons**

- **Flavor**: $\mu$, muon
- **Mass**: 0.106 GeV/c$^2$
- **Electric charge**: -1

**Leptons**

- **Flavor**: $\nu_H$, heaviest neutrino
- **Mass**: $(0.04-0.14) \times 10^{-9}$ GeV/c$^2$
- **Electric charge**: 0

**Leptons**

- **Flavor**: $\tau$, tau
- **Mass**: 1.777 GeV/c$^2$
- **Electric charge**: -1

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**Quarks**

- **Flavor**: $u$, up
- **Approx. Mass**: 0.002 GeV/c$^2$
- **Electric charge**: 2/3

**Quarks**

- **Flavor**: $d$, down
- **Approx. Mass**: 0.005 GeV/c$^2$
- **Electric charge**: -1/3

**Quarks**

- **Flavor**: $c$, charm
- **Approx. Mass**: 1.3 GeV/c$^2$
- **Electric charge**: 2/3

**Quarks**

- **Flavor**: $s$, strange
- **Approx. Mass**: 0.1 GeV/c$^2$
- **Electric charge**: -1/3

**Quarks**

- **Flavor**: $t$, top
- **Approx. Mass**: 173 GeV/c$^2$
- **Electric charge**: 2/3

**Quarks**

- **Flavor**: $b$, bottom
- **Approx. Mass**: 4.2 GeV/c$^2$
- **Electric charge**: -1/3
Look at the particle “periodic table”
It has up and down quarks which make protons and neutrons...
Which bind with electrons to make atoms...
And a neutrino, partner with electron...
So what’s all the stuff to the right?
There just appear to be three copies of all the matter that really matters...
All that distinguishes the “generations” is their mass

Three families

Who ordered THAT!?!?

--- I.I. Rabi

175,000 MeV!
Antimatter... is really weird

- All particles have antiparticles!
- Antimatter has the same properties as matter:
  - Same mass, same spin, same interactions
  - But opposite electric charge
- Has another weird property...
  - It can annihilate with matter to create pure energy!
  - Or, conversely, energy can create matter and antimatter pairs. $E=mc^2$

So you might ask: The early Universe had a lot of energy.... where is the antimatter in the Universe?
Why is the Universe made of matter?

- Good question: if the Universe started with same amount of matter and antimatter, where is the antimatter?
  - Look for annihilations
  - As far away as we can tell, today there aren’t big matter and antimatter collisions

- We don't know why this is true yet!
- Active field of research
- There must be a basic matter-antimatter asymmetry in one of the forces of Nature
How weak are Weak Interactions?

- Weak is, in fact, way weak
- A 3 MeV neutrino produced in fusion from the sun will travel through water, on average **53 light years**, before interacting
  - The 3 MeV positron (anti-matter electron) produced in the same fusion process will travel 3 cm, on average
- Moral: to find neutrinos, you need a lot of neutrinos and a lot of detector!
- Super-Kamiokande: confirms the existence of the sun in neutrino image!
  - Masatoshi Koshiba, UR PhD 1955, Nobel 2002

The Sun, imaged in neutrinos, by Super-Kamiokande, and optical
Where are neutrinos found?

- **Anywhere there are weak interactions!**
- **The early Universe**
  - The heavy things to the right decay (weakly), leaving a waste trail of $100/\text{cm}^3$ of each neutrino species
  - They are (now) very cold and **slow** and **hard** to detect
  - But if they have even a very small mass, they make up much of the weight of the Universe
- **In the sun**
  - Sun shines by fusion, energy reaching Earth in light and in neutrinos is similar
  - 100 billion neutrinos per cm$^2$ per second rain on us
- **Supernova 1987A** (150,000 light years away)
  - When it exploded, it released 100 times the neutrinos the sun will emit in its whole lifetime
  - We observed 11 neutrinos in detectors on Earth!
More neutrinos!

**Bananas?**
- We each contain about 20mg of $^{40}$K which is unstable and undergoes $\beta$ decay
- So each of us emits 0.3 billion neutrinos/sec

For the same reason, the **natural radioactivity of the Earth** results in 10 million neutrinos per cm$^2$ per second here

**Nuclear reactors** (6% of energy is anti-neutrinos)
- Average plant produces $10^{20}$ anti-neutrinos/sec

**Cosmic Rays**
- Cosmic rays from galaxy
- Each particle (mostly protons) has many GeV of energy
- Collisions in upper atmosphere create particles which decay (weakly) to neutrinos
- Can use same technique to produce neutrinos at accelerators
Cosmic shower of μ’s recorded 140 meters underground
The Strong Force…

- This force is so strong that it can effectively be thought of as glue
  - Force carrier is named the “gluon”
  - Gluons connect to “color”
  - Can think of these colors as combining like light
  - “White” (colorless) things don’t feel the strong force

- If you think of this as “glue” then these colorless combinations stick together
  - This is called “confinement”
  - The proton is one such “confined combination of quarks”
    - Red + Green + Blue → Colorless

- So two questions follow from this picture
  - What happens if you try to pull things apart?
  - How do protons stick to each other?
Fighting the strong force

- A good model for trying to pull two quarks is like putting energy into a spring
  - When it “breaks” it breaks by creating matter!
  - Separate into two “colorless” objects
- This is why free or bare quarks have never been observed
- The further away the strong force binds two quarks, the stronger it is!
  - Why? Because gluons also feel the strong force, so as distance increases, make more and more gluons
    - and quark+antiquark pairs
- Most of the mass of a proton is actually energy exchanges carried by gluons
  - Most of your mass is strong force dynamics

Quantum Chromodynamics (QCD)
Gluing together protons

Asking why two (colorless) protons are attracted by the strong force is analogous to asking how molecules bind together

- Answer is basically the residual electric force over the size of the atom. Only works if nearby.

Answer is exactly the same for strong force
- Residual strong force, but only if nearby...
Ever since Maxwell, physicists have dreamed of becoming famous by unifying descriptions of fundamental forces.

Unfortunately, the history is not encouraging...

- Einstein spent most of his late career attempting to unify gravity and electromagnetism...

The trend is not positive:

- Number of Forces: 4
  - Electricity
  - Magnetism
  - Weak Force
  - Strong Force

- Unifications: 1
  - Gravity
Unification of Forces (cont’d)

- The one exception to this trend is “electroweak” unification
  - Weak and electromagnetic force share a common description
  - Above ~100 GeV they become one force
  - Below that energy, they are distinct

- Weak force and electromagnetism are very different because the carriers of the weak force are very massive bosons (W, Z)
  - Can exchange mass over short ranges by the uncertainty principle
  - “Borrow” the energy for a short time

- How to combine a massless photon and massive W and Z?
  - Answer: The Higgs Mechanism
Higgs mechanism

- How does the Higgs work?
- Envisage the motion of people at a party...
  - Outside the party, they are free to walk
  - Inside, limited by crowd

- Now imagine a VIP enters the room...
  - A cluster of people forms around the VIP
  - Her motion is more restricted: more inertia (mass)
  - This is what happens to W, Z
  - But not to photon!
Higgs particles

- Ok, so the Higgs mechanism explains why particles acquire mass
- There are also collective excitations of the medium
- Imagine a rumor spreading...
  - The rumor *causes* people to cluster
  - This strong interaction *is like a mass*
  - The mechanism itself has mass!
  - A new particle to discover!

- This particle has not yet been observed
  - So we still don't know why particles have a mass!
  - It could be a mechanism different from the Higgs mechanism
  - But something does what the Higgs does
  - Build LHC to continue our quest for the origin of mass
The Rochester connection

2010 J.J. Sakurai Prize

"For elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses"

Peter W. Higgs
University of Edinburgh

Gerald S. Guralnik
Brown University

Robert Brout
Université Libre de Bruxelles

Carl R. Hagen
University of Rochester

François Englert
Université Libre de Bruxelles

T. W. B. Kibble
Imperial College
What about gravity?

- Unifying gravity with all the other forces is the purview of an effort in physics called “string theory”
  - It’s a very beautiful picture, but it shows the unification dynamics happening at very tiny distances
  - Roughly $10^{-35}$ m! We can’t even conceive of how to see something this small!

- Supersymmetry may get us closer to including gravity, but it is still not a complete theory
  - Like antiparticles but with spin
  - Fermion ↔ Boson