Today

• Announcements:
  – HW#10 is due April 9 at 8:00 am.
  – The Spring Break Story Winner is...

• What is matter? What is mass?
Standard Model

• The fundamental theory of nature’s constituents and their interaction is called the Standard Model.

• The theory includes:
  – Strong interactions due to the color charges of quarks and gluons.
  – A combined theory of weak (weak charge) and electromagnetic interaction (charge), known as electroweak theory.

• The theory does not include the effects of gravity. Gravity is tiny compared to the other forces and can be neglected in describing atoms.
What is matter

• Matter is the collection of objects made of baryons and leptons.

• Objects have quantum numbers that describe their nature

Electron:
Charge, lepton number, baryon number, etc.

Electrons also have mass. What is mass?
## Four Fundamental Forces

<table>
<thead>
<tr>
<th>Force</th>
<th>Particles</th>
<th>Strength</th>
<th>Range</th>
<th>Mediator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>All</td>
<td>6E-39</td>
<td>Infinite</td>
<td>Graviton</td>
</tr>
<tr>
<td>Weak</td>
<td>All</td>
<td>1E-5</td>
<td>1E-17 m</td>
<td>W±, Z⁰</td>
</tr>
<tr>
<td>Electro-magnetic</td>
<td>Charged, Charged</td>
<td>1/137</td>
<td>Infinite</td>
<td>Photon</td>
</tr>
<tr>
<td></td>
<td>Hadrons</td>
<td>1</td>
<td>1E-15 m</td>
<td>Gluon</td>
</tr>
<tr>
<td>(protons and neutrons)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Standard Model Particles

Charge

+2/3 →

-1/3 →

Anti-particles have the opposite charge.

Scalar particle(s)

Higgs
The structure of the periodic table arises from the underlying quantum numbers.
Quantum Numbers (2)

• Names like top, charm, strange, color, etc. do not mean the same things they do in everyday life. They are just identifiers.

• These names represent a set of quantum numbers that explain the number and types of particles that we observe.

• Chemistry, nuclear science, and particle physics all use different sets of quantum numbers, although they are all based on related ideas.
Rules for particle interactions

Example: \( e^- + \bar{e}^+ \rightarrow u + \bar{u} \) \ ALLOWED

\( n \rightarrow p^+ + e^- \) \ NOTALLOWED (lepton number)

\( n \rightarrow p^+ + e^- + \bar{\nu} \) \ ALLOWED

Conserved: Electric charge, lepton number \((e = +1, \ \bar{e} = -1)\), color charge, baryon number (could also count quarks: quarks +1/3, antiquarks -1/3), energy, momentum, and angular momentum.

\[ n + p^+ \rightarrow \pi^+ + \pi^+ + \pi^- \]

\[ \pi^- \rightarrow e^- + \bar{\nu} \]

The standard model explains how particles interact and transform.
What is mass

• Most mass in matter comes from energy: \( E=mc^2 \)
• The mass of the quarks that make up a proton is only a few percent of the mass. Most of the mass is in gluons (the carriers of the force).
What is mass? The interaction with a field

Space is filled with a (scalar) particle called the Higgs boson. The more a particle interacts with the Higgs field, the greater its mass is.
The Higgs is the most famous undiscovered particle. A new collider called the Large Hadron Collider may find it. The world community is spending 10 billion $ to find this.
How the Higgs will decay and be detected

(a) \[ H \rightarrow W \gamma, \quad W \rightarrow W \gamma \]

(b) \[ H \rightarrow W \gamma \]

(c) \[ H \rightarrow t \bar{t}, \quad t \rightarrow t \gamma \]
Problems with the Standard Model

- Why so many particles?
- Are there more particles we don’t know about yet?
- What is charge? Why does it come in fixed units? Same for lepton number and baryon number…
- Why is the standard model so complicated?
- Why 4 forces?
- How is gravity related to the other forces?
- In general the standard model does not answer the WHY question. Everyone agrees it is not a complete theory.
What comes next?

• There are attempts to extend the standard model to include gravity; these are called supersymmetric theories.
• These say that all fermions (which make up matter) and bosons (that transmit forces) have a corresponding partner boson (to go with our standard fermions) and fermion (to go with our standard bosons).
• Supersymmetric theories predict a whole set of new particles called s-particles, e.g. selectron, sneutrino, photino, Wino, and so on
• A new accelerator (Large Hadron Collider at CERN [Europe]) may be able to produce some of these particles in the next two years.
Superstring Theory

- One of the promising new theories is string theory. It says that the fundamental building blocks of nature are tiny \(10^{-35} \text{ m}\) strings.
- The particles we observe in nature are different ways for strings to vibrate.
- String theory is not accepted because so far it has not devised an experiment that could test it.
- String theories require at least 10 dimensions.
- Gravity is weak because the graviton exists mostly in another dimension, but there is a slight overlap with us
String Theory Pictures

Extra Dimensions

What one of the dimensions might look like (Calabi-Yau space)

Interaction of Strings:
The finite size ($10^{-35}$ m) overcomes many of the problems with the interaction of point particles.
More energy – smaller wavelength

- It is a quirk of nature that, the smaller a particle is, the greater is the energy need to see it.
- To study a particle you have to have sufficient concentrated energy to create it.
- This has fueled the construction of particle accelerators, then colliders, which have continuously increased in size.
Scale of Energy (per Particle)

- Chemistry Experiment ~0.1-5 eV
- First Cyclotron (USA) 8E4 eV
- National Superconducting Cyclotron Laboratory (USA) 1.4E8 eV
- Super Proton Synchrotron (Europe) 4E11 eV
- Relativistic Heavy Ion Collider (USA) 1E11 eV
- Tevatron (USA) 1E12 eV
- Large Hadron Collider (Europe) 7E12 eV
- [Superconducting Super Collider (USA)] 2E13 eV
Goal: Create a plasma of quarks and gluons
Tevatron – Fermilab (Illinois)

Goal: Produce the top quark
Tevatron - Fermi National Laboratory (Illinois)

Goal: Produce the top quark

Drift Tube Linac
Large Hadron Collider – CERN (Europe)

- Collisions at the Large Hadron Collider
  - 7 TeV Proton-Proton colliding beams
  - 2.7 km circumference
  - 14 TeV energy

CERN in numbers

- Financed by 20 European countries
- Special contributions also from other countries:
  - USA, Canada, China, Japan, Russia, etc.
- 1000 CHF (650 M€) budget to cover operation + new accelerators
- 2,200 staff (and diminishing)
- 6,000 users (researchers) from all over the world
  - broad visitor and fellowship program

LHC Detectors

- General-purpose
  - Higgs
  - SUSY
  - ATLAS
  - SPS
  - ALICE
  - Heavy Ions
  - Quark-gluon plasma

Accelerators and detectors in underground tunnels and caverns

Overall view of the LHC experiments.
Cost

• It is worth noting that these experiments are very expensive. The cost of a single particle:
  – Burning one carbon atom  tiny, almost free
  – Gold  small, almost free
  – Radioactive isotope ($^{64}$Fe)  ~$0.001
  – Superheavy nucleus ($^{272}$Rg)  ~$200,000
  – Higgs particle  $0.1$-$1$ billion

• How much are you/we willing to pay for a greater understanding of the universe?