Topics In Particle Physics

• Cosmic Messengers!
  – Dirac, Anderson and the Positron!
    • antimatter

• Fundamental forces in nature

• How elementary particles are produced: Accelerators

• Classification of Particle and How we know this
  – Conservation laws

• Colored Quarks and Quantum Chromodynamics!

• Electroweak theory and Standard model

• The Higgs Particle and Large Hadron Collider

• Beyond the Standard model: Supersymmetry & Strings
Fundamental Particle Physics

What are the elementary constituents of matter?

What are the forces that control their behaviour at the most basic level?
Size of Things

Instruments

- Accelerators (LHC, LEP)
- Electron Microscope
- Telescope
- Radio Telescope

Observables

- $10^{-34}$: SUSY particle (range of weak force)
- $10^{-30}$: Higgs
- $10^{-26}$: Z/W
- $10^{-22}$: Proton Nuclei
- $10^{-18}$: Atom
- $10^{-14}$: Virus
- $10^{-10}$: Cell
- $10^{-6}$: Earth radius
- $1m$: Earth to Sun
- $10^6$: Galaxies
- $10^{10}$: Radius of observable Universe
- $10^{14}$: Milky Way group
- $10^{18}$: Local supergroup
- $10^{22}$: Local group
- $10^{26}$: Milky Way

Size of Things
Probing The Cosmic Onion: Experimentally

Rutherford (1909): Nuclear atom (proton)
Chadwick (1932): Discovers neutron
SLAC (1968): Quarks in neutrons and protons
Power of Microscope

Wavelength of probe radiation should be smaller than the object to be resolved

\[ \lambda \ll \frac{h}{p} = \frac{hc}{E} \]

<table>
<thead>
<tr>
<th>Object</th>
<th>Size</th>
<th>Energy of Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atom</td>
<td>$10^{-10}$ m</td>
<td>0.00001 GeV (electrons)</td>
</tr>
<tr>
<td>Nucleus</td>
<td>$10^{-14}$ m</td>
<td>0.01 GeV (alphas)</td>
</tr>
<tr>
<td>Nucleon</td>
<td>$10^{-15}$ m</td>
<td>0.1 GeV (electrons)</td>
</tr>
<tr>
<td>Quarks</td>
<td>?</td>
<td>&gt; 1 GeV (electrons)</td>
</tr>
</tbody>
</table>

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.
Cosmic Messengers

High energy particles bombard the earth at large rate.

Discovery of new subatomic particles: Muon and positron!
\[ E^2 = (pc)^2 + (mc^2)^2 \Rightarrow E = \pm \sqrt{(pc)^2 + (mc^2)^2} \]

What does the negative energy solution imply??!

- Dirac postulated that all negative energy states were filled with electrons. They exert no net force on anything and thus are unobservable.
- Used Pauli Excl. principle to claim that only “holes” in this infinite sea of negative energy states observable.
- Holes would act as positive charge with positive energy
  - Anderson’s discovery of positron!
Discovery of Positron From Cosmic Rays
Pair Production: Photoelectric effect with a negative energy electron!

Photon with $hf > 2mc^2$ collides with the negative energy electron and excites it to a positive energy state, leaving a “hole” that appears as a positron.
Pair Production Photographed in B field: Note Curvature
All particles have an anti-matter partner!
Look Ma: Antimatter!
Forces of Nature

Electricity
Magnetism
Light
Beta decay
Neutrino interactions
Protons
Neutrons
Pions
Terrestrial gravity
Celestial mechanics
Electro-magnetism
Electroweak interactions
Weak interactions
Standard Model
Strong interactions
Universal gravitation
Spacetime geometry
General relativity

?
Quanta of Interaction

Interaction between two matter particles e.g. electrons

**Action at a distance**

\[ F \propto \frac{e^2}{r^2} \]

Newton
Force on A depends on where B is.
But how does A know where B is?

**Interaction through Fields**

Maxwell
B produces a field, characterized by a number \((e/r^2)\) at every point in space.
Force on A is towards the direction in which the number changes fastest
A determines its response by 'sniffing' in its immediate neighbourhood

BUT - still no tangible connection between A and B

**Forces are produced by exchange of force or 'messenger' particles**

Feynman:
B continually emits carriers of the electromagnetic force - 'photons' Electron A absorbs the photons and recoils - repulsive force between the electrons.
In Quantum Field Theory both signs of impulse are possible.
Forces are transmitted by the exchange of (force) particles between (matter) particles

Explains the differences between forces
To verify: look for force particles

Range of a Force $\alpha \frac{1}{\text{mass of exchange particle}}$

Observe 4 forces
There are 4 different types of force fields
The Four Fundamental Forces

**Strong**
- Gluons (8)
  - Quarks
- Mesons
- Baryons
- Nuclei

**Electromagnetic**
- Photon
- Atoms
- Light
- Chemistry
- Electronics

**Gravitational**
- Graviton ?
- Solar system
- Galaxies
- Black holes

**Weak**
- Bosons (W,Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun
## Forces in Nature

<table>
<thead>
<tr>
<th>Interaction (Force)</th>
<th>Particles Acted on by Force</th>
<th>Relative Strength$^a$</th>
<th>Typical Lifetimes for Decays via a Given Interaction</th>
<th>Range of Force</th>
<th>Force-Carrying Particle Exchanged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Quarks, hadrons</td>
<td>1</td>
<td>$\leq 10^{-20}$ s</td>
<td>Short ($\approx 1$ fm)</td>
<td>Gluon</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Charged particles</td>
<td>$\approx 10^{-2}$</td>
<td>$\approx 10^{-16}$ s</td>
<td>Long ($\infty$)</td>
<td>Photon</td>
</tr>
<tr>
<td>Weak</td>
<td>Quarks, leptons</td>
<td>$\approx 10^{-6}$</td>
<td>$\geq 10^{-10}$ s</td>
<td>Short ($\approx 10^{-3}$ fm)</td>
<td>$W^\pm, Z^0$ bosons</td>
</tr>
<tr>
<td>Gravitational</td>
<td>All particles</td>
<td>$\approx 10^{-43}$</td>
<td>?</td>
<td>Long ($\infty$)</td>
<td>Graviton$^b$</td>
</tr>
</tbody>
</table>

$^a$For two $u$ quarks at $3 \times 10^{-17}$ m.

$^b$Not experimentally detected.