Lecture on

PARTICLE PHYSICS

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Lecture contents

- **Section-1**: Basics of elementary particle physics
- **Section-2**: Fundamental interactions/forces
- **Section-3**: Conservation laws & Symmetries
- **Section-4**: Building blocks of matter
- **Section-5**: Conclusion with the Fundamental Model of particles
Section-1: Basics of elementary particle physics

Some open questions for students:

• What is Particle Physics and why do we study it?
• What are the Elementary particles?
• What are the basic building blocks of matter in the Universe?
• What are fundamental forces and how are they transmitted?
• What is the world made of?
• What is the origin of mass?
• What do the theories underlying particle physics look like?
• How much matter present in the universe?
• What does this tell us about the origins of the Universe?
Elementary Particle Physics:

✓ Elementary particle physics studies the fundamental building blocks of nature. But what fundamental does mean? By fundamental we mean objects that are simple and structureless, not made of anything smaller.

✓ During the past century the word “fundamental” was addressed firstly to the atom. The word “atom” was introduced by Democritus (400 BC) who described the matter as composed by small and indivisible particles (“atom” comes from greek a-temno, which can not be divided).

✓ The internal structure of the atom was discovered and protons, neutrons and electrons became the building blocks of matter.

✓ After 1960, scattering experiments of high energy particles on nucleons lead to the discovery of the quarks, which are thought now as the fundamental consituents of matter.
Sub-atomic dimensions

Everyday Objects are made of Molecules.
Molecules are made of Atoms.
Atoms are made of Nuclei and Electrons.
Nuclei are made of Protons and Neutrons.
Protons and Neutrons are made of Quarks.
Quarks and Electrons are made of ???

Quarks and Electrons are "Elementary Particles"
How small is small?

- $10^{-7} \text{ m}$: virus
- $10^{-9} \text{ m}$: molecule
- $10^{-10} \text{ m}$: atom
- $10^{-14} \text{ m}$: nucleus
- $10^{-15} \text{ m}$: proton/neutron
- $<10^{-18} \text{ m}$: quarks
Is it deal with Quantum Physics?
At the beginning just a few…
A Journey of Particles:

Question: How can we classify all fundamental particles?

Higgs Bosons
2012
And many others…
**Mesons:** Pi-meson, K-meson, eta-meson

**Baryons:** Proton, neutron, hyperons

**Elementary Particles**

- **Elementary fermions**
  - Half-integer spin, Obey the Fermi–Dirac statistics
  - Quarks and antiquarks
    - Spin = \( \frac{1}{2} \)
    - Have color charge
    - Participate in strong interactions
    - Three Generations
      1. Up (u), Down (d)
      2. Charm (c), Strange (s)
      3. Top (t), Bottom (b)

- **Elementary bosons**
  - Integer spin, Obey the Bose–Einstein statistics
  - Leptons and anti-leptons
    - Spin = \( \frac{1}{2} \)
    - No color charge
    - Electroweak interactions
    - Three Generations
      1. Electron, Electron neutrino
      2.Muon, Muon neutrino
      3. Tau, Tau neutrino

- **Gauge bosons**
  - Spin = 1
  - Force carriers

- **Scalar bosons**
  - Spin = 0

**Four kinds**
(four fundamental interactions)

1. Photon
   (γ, electromagnetic interaction)
2. W and Z bosons
   (W⁺, W⁻, Z, weak interaction)
3. Eight types of gluons
   (g, strong interaction)
4. Graviton
   (G, gravity, hypothetical)

**Unique**
Higgs boson (H⁰)
Particle classification according to acting interactions:

- **Leptons** – interact weakly and charged also electromagnetically, they do not interact strongly \((e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau)\) – in the present experiments they are point like

- **Hadrons** – interact in addition also strongly – they have structure and size \(\approx 1\ \text{fm}\)

Particle classification according to statistics:

- **Bosons**: Bose-Einstein statistic \(\rightarrow\) arbitrary number of particles in given state – integral spin
  Wave function – symmetric:
  \[\Psi_B(x_1, x_2, \ldots, x_n) = \Psi_B(x_2, x_1, x_3, \ldots, x_n)\]

- **Fermions**: Fermi-Dirac statistic \(\rightarrow\) Pauli exclusion principle \(\rightarrow\) only one identical particle in given state – half-integral spin. Wave function is antisymmetric:
  \[\Psi_F(x_1, x_2, x_3, \ldots, x_n) = -\Psi_F(x_2, x_1, x_3, \ldots, x_n)\]
Strange Particles:

- Produce through the strong interaction and decay through the weak interaction.
- None of the product particle i.e. neutrino or anti-neutrino in weak interaction (unlike as beta decay)
- Production time is very fast and decay time is very slow (it is very interacting property).
- $T_p = \text{less than 1 sec. } T_d = 3000 \text{ years (approx.)}$
- $K −\text{mesons, } \Lambda, \Sigma, \Xi, \Omega −\text{hyperons are called strange particles.}$
- These particles have additional quantum number called “Strangeness”.
What is the difference between a force and an interaction?

- This is a hard distinction to make. Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through.

- The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, although "interaction" is more correct.

- You will usually be okay using the terms interchangeably, but you should know that they are different.
One of the main goals of particle physics is to unify these forces (to show that they’re all just different aspects of the same force), just as Maxwell did for the electric and magnetic forces many years earlier.
### Summary of fundamental forces in nature:

<table>
<thead>
<tr>
<th>Name</th>
<th>Acts on:</th>
<th>Carrier</th>
<th>Range</th>
<th>Strength</th>
<th>Stable systems</th>
<th>Induced reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>all particles</td>
<td>graviton</td>
<td>long</td>
<td>$\sim 10^{-39}$</td>
<td>Solar system</td>
<td>Object falling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$F \propto 1/r^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak force</td>
<td>fermions</td>
<td>bosons W and Z</td>
<td>&lt; $10^{-17}$ m</td>
<td>$10^{-5}$</td>
<td>None</td>
<td>$\beta$-decay</td>
</tr>
<tr>
<td>Electromagnetism</td>
<td>particles with electric charge</td>
<td>photon</td>
<td>long</td>
<td>$1/137$</td>
<td>Atoms, stones</td>
<td>Chemical reactions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$F \propto 1/r^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong force</td>
<td>quarks and gluons</td>
<td>gluons</td>
<td>$10^{-15}$ m</td>
<td>$1$</td>
<td>Hadrons, nuclei</td>
<td>Nuclear reactions</td>
</tr>
</tbody>
</table>

**Question:** How can we calculate the ‘Range’ of forces?
Fifth fundamental forces: A scientific approach

✓ Some speculative theories have proposed a fifth fundamental force to explain various anomalous observations that do not fix existing theories.

✓ It is hypothetical force, not observed yet

✓ Most Scientists believe that this force helps us to explain that most of the universe is accounted for by an unknown form of matter called dark matter.

✓ It require extra dimensions to formulate.
Range of forces:

✓ The range of forces is related to the mass of exchange particle \( M \).

✓ An amount of energy \( \Delta E = Mc^2 \) borrowed for a time \( \Delta t \) is governed by the Heisenberg’s Uncertainty Principle:

\[
\Delta E \times \Delta t \sim \hbar
\]

✓ The maximum distance the particle can travel is \( \Delta x = c \Delta t \), where \( c \) is speed of light.

\[
\Delta x = \frac{\hbar c}{\Delta E}
\]

✓ Exp: The photon has \( M = 0 \) ---- \( \Rightarrow \) infinite range of EM force

\( W \) boson has a mass of \( 80 \, \text{GeV}/c^2 \) \( \Rightarrow \) Range of weak force is about \( 2 \times 10^{-3} \, \text{fm} \)
Which forces act on which particles?

- The weak force acts between all quarks and leptons
- The electromagnetic force acts between all charged particles
- The strong force acts between all quarks (i.e. objects that have color charge)
- Gravity does not play any role in particle physics

<table>
<thead>
<tr>
<th></th>
<th>Weak</th>
<th>EM</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quarks</strong></td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Charged leptons</strong></td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Neutral leptons</strong></td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Section-3: Conservation laws & Symmetries

✓ Conservation laws are fundamental to our understanding of the physical world, in that they describe which processes can or cannot occur in nature.

✓ Exact conservation laws include conservation of energy, conservation of linear momentum, conservation of angular momentum, and conservation of electric charge.

✓ There are also many approximate conservation laws in particle physics, which apply to such quantities as parity, charge conjugation, time reversal, lepton number, baryon number, strangeness, hypercharge, isospin etc.

✓ One particularly important result concerning conservation laws is Noether's theorem, which states that there is a one-to-one correspondence between each one of them and a differentiable symmetry of nature.
<table>
<thead>
<tr>
<th>Conservation Law</th>
<th>Respective Noether’s symmetry invariance</th>
<th>Meaning of invariance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservation of energy</td>
<td>Time invariance</td>
<td>translation about time axis</td>
</tr>
<tr>
<td>Conservation of linear momentum</td>
<td>Translation symmetry</td>
<td>translation about $x,y,z$ position</td>
</tr>
<tr>
<td>Conservation of angular momentum</td>
<td>Rotation invariance</td>
<td>rotation about $x,y,z$ axes</td>
</tr>
<tr>
<td>CPT symmetry (combining charge conjugation, parity and time reversal)</td>
<td>Lorentz invariance</td>
<td>(charge inversion $q \rightarrow -q$) +</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(position inversion $r \rightarrow -r$) +</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(time inversion $t \rightarrow -t$)</td>
</tr>
<tr>
<td>Conservation of electric charge</td>
<td>Gauge invariance</td>
<td>scalar field (1D) in 4D spacetime $x,y,z$ + time evolution</td>
</tr>
<tr>
<td>Conservation of color charge</td>
<td>SU(3) Gauge invariance</td>
<td>$r,g,b$</td>
</tr>
<tr>
<td>Conservation of weak isospin</td>
<td>SU(2), Gauge invariance</td>
<td>weak charge</td>
</tr>
<tr>
<td>Conservation of probability</td>
<td>Probability invariance</td>
<td>total probability always = 1 in $x,y,z$ space, during time evolution</td>
</tr>
</tbody>
</table>
Symmetries:

✓ A symmetry is a physical or mathematical feature of the system that remains unchanged under some transformation.

✓ **Global or Local Symmetries (broadly classified):** A *global symmetry* is one that holds at all points of spacetime, whereas a *local symmetry* is one that has a different symmetry transformation at different points of spacetime.

✓ **Discrete and Continuous Symmetries:** The quadratic one has a discrete symmetry w.r.t. rotation along its axis, while the round one enjoys a continuous symmetry.
<table>
<thead>
<tr>
<th>Class</th>
<th>Invariance</th>
<th>Conserved quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lorentz symmetry</strong></td>
<td>translation in time</td>
<td>energy</td>
</tr>
<tr>
<td></td>
<td>(homogeneity)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>translation in space</td>
<td>linear momentum</td>
</tr>
<tr>
<td></td>
<td>(homogeneity)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>rotation in space</td>
<td>angular momentum</td>
</tr>
<tr>
<td></td>
<td>(isotropy)</td>
<td></td>
</tr>
<tr>
<td><strong>Discrete symmetry</strong></td>
<td>P, coordinate inversion</td>
<td>spatial parity</td>
</tr>
<tr>
<td></td>
<td>C, charge conjugation</td>
<td>charge parity</td>
</tr>
<tr>
<td></td>
<td>T, time reversal</td>
<td>time parity</td>
</tr>
<tr>
<td></td>
<td><strong>CPT</strong></td>
<td>product of parities</td>
</tr>
<tr>
<td><strong>Internal symmetry</strong></td>
<td><strong>U(1) gauge transformation</strong></td>
<td>electric charge</td>
</tr>
<tr>
<td>(independent of spacetime coordinates)</td>
<td><strong>U(1) gauge transformation</strong></td>
<td>hypercharge</td>
</tr>
<tr>
<td></td>
<td><strong>U(1)_Y gauge transformation</strong></td>
<td>weak hypercharge</td>
</tr>
<tr>
<td></td>
<td><strong>SU(2) gauge transformation</strong></td>
<td>isospin</td>
</tr>
<tr>
<td></td>
<td><strong>SU(2)_L gauge transformation</strong></td>
<td>weak isospin</td>
</tr>
<tr>
<td></td>
<td><strong>SU(3) gauge transformation</strong></td>
<td>quark color</td>
</tr>
<tr>
<td></td>
<td><strong>SU(3) (approximate)</strong></td>
<td>quark flavor</td>
</tr>
<tr>
<td></td>
<td>[ <strong>U(1) × SU(2) × SU(3)</strong> ]</td>
<td>Standard Model</td>
</tr>
</tbody>
</table>
CPT-Theorem:

✓ **Parity (P):** The conservation of parity $P$ describes the inversion symmetry of space, 
\[
\bar{x} \rightarrow -x; \quad \bar{y} \rightarrow -y, \quad \text{and} \quad \bar{z} \rightarrow -z
\]

✓ **Charge conjugation (C):** It has the effect of interchanging every particle with its antiparticle.

✓ **Time Reversal (T):** Here time $t$ is replaced with $-t$.

✓ **CPT Theorem:** Georg Ludens, Wolfgang Pauli and Julian Schwinger independently showed that invariance under Lorentz transformations implies CPT invariance.

It states that if a quantum field theory is invariant under Lorentz transformation, then $CP T$ is an exact symmetry !!

( Note that if, for example, CP is violated, then $T$ must be violated )
Some conservation numbers:

- **Baryon Conservation**: The conservation of baryon number requires the same total baryon number before and after the reaction. The value $B = +1$ for baryons and $-1$ for antibaryons, and 0 for all other particles. *(See: Neutron & anti-neutron?)*

- **Lepton Conservation**: The number of leptons from each family is the same both before and after a reaction. We let $L_e = +1$ for the electron and the electron neutrino; $L_e = -1$ for their antiparticles; and $L_e = 0$ for all other particles. We assign the quantum numbers $L_\mu$ for the muon and its neutrino and $L_\tau$ for the tau and its neutrino similarly. See beta decay: $n \rightarrow p + e + \bar{\nu}_e$ *(Why anti-electron neutrino here?)*

- **Strangeness Conservation**: The kaons have $S = +1$, lambda and sigmas have $S = -1$, the xi has $S = -2$, and the omega has $S = -3$.

- **Isospin Conservation**: The isotropic spin, makes out that proton and neutron are two charge states of a single particle nucleon. $I = 1/2$ for nucleon and $I_3 = +1/2$ for proton and $I_3 = -1/2$ for neutron.
## Conservation Laws

<table>
<thead>
<tr>
<th>Property</th>
<th>Strong</th>
<th>E.M.</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Momentum</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Electric Charge</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Baryon Number</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Lepton Number</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Isospin (I)</td>
<td>✔</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Strangeness (S)</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Charm (C)</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Parity (P)</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Charge Conjugation (C)</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>CP (or T)</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>CPT</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
### Physical quantities for particle and antiparticle:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>particle</th>
<th>antiparticle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass $m$</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Spin (magnitude)</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Lifetime $\tau$</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Isospin (magnitude)</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Electric charge</td>
<td>$Q$</td>
<td>$-Q$</td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>$\mu$</td>
<td>$-\mu$</td>
</tr>
<tr>
<td>Baryon number</td>
<td>$B$</td>
<td>$-B$</td>
</tr>
<tr>
<td>Lepton number</td>
<td>$L$</td>
<td>$-L$</td>
</tr>
<tr>
<td>Strangeness</td>
<td>$S$</td>
<td>$-S$</td>
</tr>
<tr>
<td>$z$ component of isospin</td>
<td>$I_z$</td>
<td>$-I_z$</td>
</tr>
<tr>
<td>Intrinsic parity $P$</td>
<td>Same for bosons</td>
<td>Opposite - fermions</td>
</tr>
</tbody>
</table>
## Some particles and their properties

<table>
<thead>
<tr>
<th>Category</th>
<th>Particle Name</th>
<th>Symbol</th>
<th>Anti-particle</th>
<th>Mass (MeV/c(^2))</th>
<th>(B)</th>
<th>(L_\ell)</th>
<th>(L_\mu)</th>
<th>(L_\tau)</th>
<th>(S)</th>
<th>Lifetime(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptons</strong></td>
<td>Electron</td>
<td>(e^-)</td>
<td>(e^+)</td>
<td>0.511</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td>Electron-neutrino</td>
<td>(\nu_e)</td>
<td>(\bar{\nu}_e)</td>
<td>&lt; 7 eV/c(^2)</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td>Muon</td>
<td>(\mu^-)</td>
<td>(\mu^+)</td>
<td>105.7</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>(2.20 \times 10^{-6})</td>
</tr>
<tr>
<td></td>
<td>Muon-neutrino</td>
<td>(\nu_\mu)</td>
<td>(\bar{\nu}_\mu)</td>
<td>&lt; 0.3</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td>Tau</td>
<td>(\tau^-)</td>
<td>(\tau^+)</td>
<td>1784(\pm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>&lt;4 \times 10^{-13}</td>
</tr>
<tr>
<td></td>
<td>Tau-neutrino</td>
<td>(\nu_\tau)</td>
<td>(\bar{\nu}_\tau)</td>
<td>&lt; 30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td><strong>Hadrons</strong></td>
<td>Pion</td>
<td>(\pi^+)</td>
<td>(\pi^-)</td>
<td>139.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(2.60 \times 10^{-8})</td>
</tr>
<tr>
<td></td>
<td>(\pi^0)</td>
<td>Self</td>
<td>Self</td>
<td>135.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(0.89 \times 10^{-16})</td>
</tr>
<tr>
<td></td>
<td>Kaon</td>
<td>(K^+)</td>
<td>(K^-)</td>
<td>493.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>(1.24 \times 10^{-8})</td>
</tr>
<tr>
<td></td>
<td>(K^0)</td>
<td>(\bar{K}^0)</td>
<td>(K^0)</td>
<td>495.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>(0.89 \times 10^{-10})</td>
</tr>
<tr>
<td></td>
<td>(K^\pm)</td>
<td>(K^\mp)</td>
<td>(K^\pm)</td>
<td>497.7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>(5.2 \times 10^{-8})</td>
</tr>
<tr>
<td><strong>Baryons</strong></td>
<td>Proton</td>
<td>(p)</td>
<td>(\bar{p})</td>
<td>938.3</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Stable</td>
</tr>
<tr>
<td></td>
<td>Neutron</td>
<td>(n)</td>
<td>(\bar{n})</td>
<td>939.6</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(6 \times 10^{-4})</td>
</tr>
<tr>
<td></td>
<td>Lambda</td>
<td>(\Lambda^0)</td>
<td>(\Lambda^0)</td>
<td>1115.6</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(2.6 \times 10^{-10})</td>
</tr>
<tr>
<td></td>
<td>Sigma</td>
<td>(\Sigma^+)</td>
<td>(\Sigma^-)</td>
<td>1189.4</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(0.80 \times 10^{-10})</td>
</tr>
<tr>
<td></td>
<td>(\Sigma^0)</td>
<td>(\Sigma^0)</td>
<td>(\Sigma^0)</td>
<td>1192.5</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(6 \times 10^{-10})</td>
</tr>
<tr>
<td></td>
<td>(\Sigma^-)</td>
<td>(\Sigma^-)</td>
<td>(\Sigma^-)</td>
<td>1197.3</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(1.5 \times 10^{-10})</td>
</tr>
<tr>
<td></td>
<td>Delta</td>
<td>(\Delta^{++})</td>
<td>(\Delta^{--})</td>
<td>1239</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(6 \times 10^{-24})</td>
</tr>
</tbody>
</table>
Example: In the following pairs of proposed reactions, determine which ones are allowed and the relevant force at work

<table>
<thead>
<tr>
<th>Interaction:</th>
<th>strong</th>
<th>weak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>π⁻ + p → Σ⁰ + η⁰</strong></td>
<td>-1 + 1 = 0 + 0</td>
<td>-1 = -1 + 0</td>
</tr>
<tr>
<td><strong>π⁻ + p → Σ⁰ + K⁰</strong></td>
<td>-1 + 1 = 0 + 0</td>
<td>-1 = 1 + 1</td>
</tr>
<tr>
<td><strong>Σ⁻ → π⁻ + n</strong></td>
<td>0 = 0 + 0</td>
<td>0 = 0 + 0</td>
</tr>
<tr>
<td><strong>Σ⁻ → π⁻ + p</strong></td>
<td>1 = 0 + 1</td>
<td>1 = 0 + 1</td>
</tr>
<tr>
<td><strong>charge:</strong></td>
<td>-1 + 1 = 0 + 0</td>
<td>-1 = -1 + 0</td>
</tr>
<tr>
<td><strong>lepton number:</strong></td>
<td>0 + 0 = 0 + 0</td>
<td>0 = 0 + 0</td>
</tr>
<tr>
<td><strong>baryon number:</strong></td>
<td>0 + 1 = 1 + 0</td>
<td>1 = 0 + 1</td>
</tr>
<tr>
<td><strong>strangeness:</strong></td>
<td>0 + 0 = -1 + 0</td>
<td>0 + 0 = -1 + 1</td>
</tr>
<tr>
<td><strong>Isospin (I₃):</strong></td>
<td>-1 + 1/2 = 0 + 0</td>
<td>-1 + 1/2 = 0 - 1/2</td>
</tr>
</tbody>
</table>
Section-4: Building blocks of matter

What is the world made of?

• Real world is not done by single quarks

• Quarks exist only in groups, to form the so-called hadrons (protons and neutrons are hadrons)

• Example: a proton is made of two quarks of up type and one quark of type down.

• The matter around, and even each of us, is made of quarks and of leptons.
What is Quark?

- Today we know that protons and neutrons are not fundamental units.
- They are made of smaller particles called **quarks**.
- For the moment, looks like quarks are point like.

Types of Quark: (i) flavors quarks  
(ii) Colour quarks
The **quark model** is a classification scheme for hadrons in terms of their **valence quarks** — the quarks and antiquarks which give rise to the quantum numbers of the hadrons.

The quark model in its modern form was developed by **Murray Gell-Mann** - American physicist who received the 1969 Nobel Prize in physics for his work on the theory of elementary particles.

* QM - independently proposed by George Zweig

Hadrons are not *fundamental*, but they are built from *valence quarks*, i.e. quarks and antiquarks, which give the quantum numbers of the hadrons.

\[ |\text{Baryon}\rangle = |qqq\rangle \quad |\text{Meson}\rangle = |qq\rangle \]

q= quarks, \( \bar{q} \) - antiquarks

Meson (q\(\bar{q}\))

Baryon (qqq)
Quark quantum numbers

The quark quantum numbers:

- **flavor (6):** u (up-), d (down-), s (strange-), c (charm-), t (top-), b (bottom-) quarks

  anti-flavor for anti-quarks \( \bar{q} : \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{t}, \bar{b} \)

- **charge:** \( Q = -1/3, +2/3 \) (u: 2/3, d: -1/3, s: -1/3, c: 2/3, t: 2/3, b: -1/3 )

- **baryon number:** \( B=1/3 \) - as baryons are made out of three quarks

- **spin:** \( s=1/2 \) - quarks are the fermions!

- **strangeness:** \( S_\uparrow = -1, \ S_\downarrow = 1, \ S_q = 0 \) for \( q = u, d, c, t, b \) (and \( \bar{q} \))

- **charm:** \( C_\uparrow = 1, \ C_\downarrow = -1, \ C_q = 0 \) for \( q = u, d, s, t, b \) (and \( \bar{q} \))

- **bottomness:** \( B_\uparrow = -1, \ B_\downarrow = 1, \ B_q = 0 \) for \( q = u, d, s, c, t \) (and \( \bar{q} \))

- **topness:** \( T_\uparrow = 1, \ T_\downarrow = -1, \ T_q = 0 \) for \( q = u, d, s, c, b \) (and \( \bar{q} \))

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Quark quantum numbers

The quark quantum numbers:

hypercharge: \[ Y = B + S + C + B + T \]  \hspace{1cm} (1)

\( (= \text{baryon charge} + \text{strangeness} + \text{charm} + \text{bottomness} + \text{topness}) \)

- \( I_3 \) (or \( I_2 \) or \( T_3 \)) - 3`d component of isospin

charge (Gell-Mann–Nishijima formula):

\[ Q = I_3 + Y/2 \]  \hspace{1cm} (2)

\( (= \text{3`d component of isospin} + \text{hypercharge}/2) \)
### Quark quantum numbers

<table>
<thead>
<tr>
<th>Property</th>
<th>Quark</th>
<th>(d)</th>
<th>(u)</th>
<th>(s)</th>
<th>(c)</th>
<th>(b)</th>
<th>(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q – electric charge</td>
<td></td>
<td>(-\frac{1}{3})</td>
<td>(+\frac{2}{3})</td>
<td>(-\frac{1}{3})</td>
<td>(+\frac{2}{3})</td>
<td>(-\frac{1}{3})</td>
<td>(+\frac{2}{3})</td>
</tr>
<tr>
<td>I – isospin</td>
<td></td>
<td>(+\frac{1}{2})</td>
<td>(+\frac{1}{2})</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I(_z) – isospin (z)-component</td>
<td></td>
<td>(-\frac{1}{2})</td>
<td>(+\frac{1}{2})</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S – strangeness</td>
<td></td>
<td>0</td>
<td>0</td>
<td>(-1)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C – charm</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(+1)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(B) – bottomness</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(-1)</td>
<td>0</td>
</tr>
<tr>
<td>(T) – topness</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(+1)</td>
</tr>
</tbody>
</table>
**Protons and neutrons in the quark model**

**Question:** Why proton has positive and neutron has neutral charge?

*Quarks have fractional electric charge!*

- **u** electric charge $+\frac{2}{3}$
- **d** electric charge $-\frac{1}{3}$

**Proton (charge +1)**

$$u\left(\frac{2}{3}\right)u\left(\frac{2}{3}\right)d\left(-\frac{1}{3}\right) = p(+1)$$

**Neutron (charge 0)**

$$u\left(\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right) = n(0)$$
Eightfold Way

The quark model is the follow-up to the Eightfold Way classification scheme (proposed by Murray Gell-Mann and Yuval Ne'eman).

The Eightfold Way may be understood as a consequence of flavor symmetries between various kinds of quarks. Since the strong nuclear force affects quarks the same way regardless of their flavor, replacing one flavor of a quark with another in a hadron should not change its mass very much. Mathematically, this replacement may be described by elements of the SU(3) group.

Consider u, d, s quarks:
⇒ then the quarks lie in the fundamental representation, 3 (called the triplet) of the flavour group SU(3): [3]

The antiquarks lie in the complex conjugate representation $\bar{3}$: [3]
Representation of SU(3) flavor of quarks

**triplet in SU(3)_{flavor} group:** $[3]$

**anti-triplet in SU(3)_{flavor} group:** $\overline{[3]}$

\[
Y = 2(Q - T_3)
\]
Mesons in the Quark model

\[ |\text{Meson} \rangle = |\bar{q}q \rangle \]

Quark triplet in \( SU(3)_{\text{flavor}} \) group: [3]

Anti-quark anti-triplet in \( SU(3)_{\text{flavor}} \) group: \([\bar{3}]\)

From group theory: the nine states (nonet) made out of a pair can be decomposed into the trivial representation, 1 (called the singlet), and the adjoint representation, 8 (called the octet).

\[ [3] \otimes [\bar{3}] = [8] \oplus [1] \]

octet + singlet
Baryons in the Quark model

\[ |\text{Baryon} \rangle = |\text{qqq} \rangle \]

Quark triplet in \( \text{SU}(3)_{\text{flavor}} \) group: \([3]\)

Eqs. (4-8): \textit{state function for baryons} – \textit{antisymmetric} under interchange of two quarks:

\[ \Psi_A \equiv |\text{qqq} \rangle_A = [|\text{color} \rangle \otimes |\text{space} \rangle \otimes |\text{spin} \rangle \otimes |\text{flavor} \rangle]_A \]

where \( |\text{flavor} \rangle \) state can be symmetric (S), antisymmetric (A) or mixed symmetry (M)

\textbf{From group theory:} with three flavours, the decomposition in flavour is

\[
\]

\[= ([6]_S \otimes [3]) \oplus ([\bar{3}] \otimes [3]) =
\]

\[= [10]_S \oplus [8]_M \oplus [8]_M \oplus [1]_A
\]

The \textbf{decuplet is symmetric in flavour, the singlet antisymmetric} and the \textbf{two octets} have \textbf{mixed symmetry} (they are connected by a unitary transformation and thus describe the same states).
Baryons in the Quark model

1) Combine first 2 quark triplets:

\[ [3] \otimes [3] = [6]_S \oplus [\bar{3}]_A \]

2) Add a 3\textsuperscript{d} quark:

\[ [3] \otimes [3] \otimes [3] = ([6]_S \oplus [\bar{3}]_A) \otimes [3] = [10]_S \oplus [8]_M \oplus [8]_M \oplus [1]_A \]
Baryonic Octet and Decuplet

Octet [8]

Decuplet [10]

Spin:

\[ J=S, \quad L=0 \]

\[ J^P = \frac{1^+}{2} \]

\[ J=S+L, \quad L=1 \]

\[ J^P = \frac{3^+}{2} \]
**Color Quarks**

**The quark quantum numbers:**

- **Collor 3:** red, green and blue \(\Rightarrow\) triplet in \(SU(3)_{\text{collor}}\) group: \([3]\)
  
  **Anticollor 3:** antired, antigreen and antiblue \(\Rightarrow\) anti-triplet in \(SU(3)_{\text{collor}}\) group \(\bar{[3]}\)

- The quark colors (red, green, blue) combine to be **colorless**
- The quark anticolors (antired, antigreen, antiblue) also combine to be **colorless**

  **All hadrons** \(\Rightarrow\) **color neutral** = **color singlet** in the \(SU(3)_{\text{collor}}\) group

**History:** The quantum number 'color' has been introduced (idea from Greenberg, 1964) to describe the state \(\Delta^{++}(uuu)\) (\(Q=+2, J=3/2\)), discovered by Fermi in 1951 as \(\pi^+p\) resonance: \(\Delta^{++}(uuu) \rightarrow p(udd) + \pi^+(du)\)

The state \(\Delta^{++}(u^u u^u u^u)\) with all parallel spins (to achieve \(J=3/2\)) is forbidden according to the Fermi statistics (without color)!
The theory of the strong interaction, Quantum Chromodynamics (QCD), is very similar to QED but with 3 conserved “colour” charges.

**In QED:**
- the electron carries one unit of charge $-e$
- the anti-electron carries one unit of anti-charge $+e$
- the force is mediated by a massless “gauge boson” – the photon

**In QCD:**
- quarks carry colour charge: $r, g, b$
- anti-quarks carry anti-charge: $ar{r}, ar{g}, ar{b}$
- The force is mediated by massless gluons

In QCD, the strong interaction is invariant under rotations in colour space

$$r \leftrightarrow b; \quad r \leftrightarrow g; \quad b \leftrightarrow g$$

i.e. the same for all three colours

This is an exact symmetry, unlike the approximate uds flavour symmetry discussed previously.
It is believed (although not yet proven) that all observed free particles are “colourless”
• i.e. never observe a free quark (which would carry colour charge)
• consequently quarks are always found in bound states colourless hadrons

**Colour Confinement Hypothesis:**

- All hadrons must be “colourless” i.e. colour singlets
- To construct colour wave-functions for hadrons, replace SU(3) flavour symmetry into SU(3) colour symmetry

![Diagram](image)

- Just as for uds flavour symmetry can define colour ladder operators
Physicists have found hundreds of new particles.
Today we know that most of them are not fundamental.

Now, question arises:
What is the Fundamental Model in particle physics?

A theory has been developed that seems to explain quite well what we do observe in nature: the theory is called **Standard Model (SM)**.
The Standard Model

Matter:
- 6 quarks
- 6 leptons
Grouped in three generations

Forces:
- Electroweak:
  - $g$ (photon)
  - $Z^0$, $W^\pm$
- Strong
  - $g$ (gluon)

Framework which includes:

The best theoretical framework we have for particle physics today

Not gravity! No quantum field theory of gravity.
Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles). The Standard Model is composed of several parts:

- **Fermions**: Matter constituents; charge spin of 1/2, 3/2, 5/2, etc.
- **Bosons**: Force carriers; charge spin of 0, 1, 2, etc.

Properties of the Interactions

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

**Unresolved Mysteries**

Driven by new puzzles in our understanding of the physical world, particle physicists are looking for new particles and new forces to explain the universe. Each unsolved question is a new step in understanding the nature of matter and energy.

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24-Jul-20
Composition of the Universe

Graphics courtesy: NASA
Mysteries, failures and new approach

✓ The SM is a theory of the Universe.

✓ It gives a good description of the phenomena which we observe experimentally.

✓ But under many respects it is an incomplete model to explain:

  • What is the dark matter and dark matter?
  • What about gravity?
  • How can we unify all fundamental forces?
  • Existence of anti-matter in the universe?
  • Origin of Big-Bang? Etc…

Advance problems in Particle Physics

Physics Beyond the Standard Model

The String Theory
Suggested books:

- “Introduction to Elementary Particles”, By D. Griffiths
- “Quarks & Leptons”, By F. Halzen & A. Martin
- “The Experimental Foundations of Particle Physics”, By R. Cahn & G. Goldhaber
- “Gauge Theories in Particle Physics”, By I.J.R. Aitchison & A.J.G. Hey
- “Introduction to High Energy Phyics”, By D.H. Perkins
Thank you for the attention!

For any queries or questions, students can contact me on the given email id:

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