Introduction to Elementary Particle Physics

Néda Sadooghi

Department of Physics
Sharif University of Technology
Tehran - Iran

Elementary Particle Physics

Lecture 14: Farvardin 24, 1398

1397-98-II

The four (three) forces

C. Weak interaction

Weak processes:

There are therefore two kinds of weak processes:

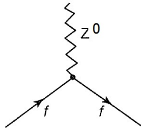
a. **Neutral weak processes** mediated by Z^0 gauge boson

b. **Charged weak processes** mediated by W^+ and W^- gauge bosons

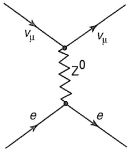
Lecture 14

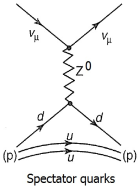
a. Neutral weak processes:

- Primitive vertex [*f* can be any lepton or any quark]



Examples: $\nu_\mu + e^- \to \nu_\mu + e^-$ and $\nu_\mu + p \to \nu_\mu + p$





Since neutrinos are involved, there is no competing EM mechanism possible

- Any process mediated by photon could also be mediated by Z^0

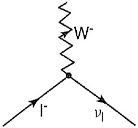
Examples: $e^- + e^+ \to e^- + e^+$ and $e^- + e^+ \to \mu^- + \mu^+$ scatterings

Lecture 14

b. Charged weak processes:

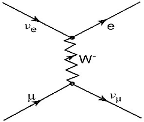
There are weak interaction of

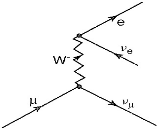
b.1 **Leptons:** A negative lepton converts into the corresp. neutrino with emission of W^- ($\ell^- \to \nu_\ell + W^-$) or absorption of W^+ ($\ell^- + W^+ \to \nu_\ell$)



Note: At each vertex, the members of one and the same generation appear

Examples: $\mu^- + \nu_e \to \nu_\mu + e^-$ or $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$





b. Charged weak processes:

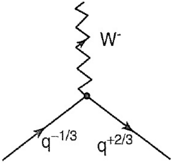
There are weak interaction of

b.2 Quarks: Flavor changing weak processes involving quarks with the same color charge by different flavor ($q^{-1/3} \rightarrow W^- + q^{2/3}$):

Note: qs are in the same generation (see later)

$q = +2/3$: u, c, t

$q = -1/3$: d, s, b

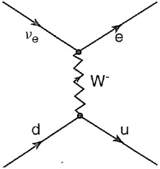


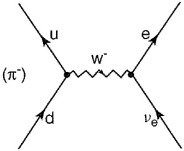
On the other side, W^- couples to

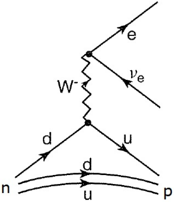
- a lone pair → **Semileptonic processes**
  Ex.: $d + \nu_e \rightarrow u + e^-$, $\pi^-(d\bar{u}) \rightarrow e^- + \bar{\nu}_e$ or $\pi^-(d\bar{u}) \rightarrow \mu^- + \bar{\nu}_\mu$ and $n \rightarrow p + e^- + \bar{\nu}_e$ (see next page)
- a quark pair → **Pure hadronic processes**
  Ex.: $\Delta^0 \rightarrow p^+ + \pi^-$

b. Charged weak processes:

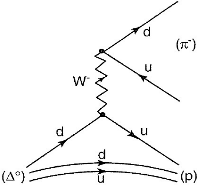
b.2.1 Semileptonic processes:



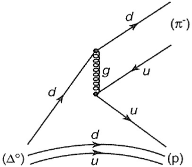




b.2.2 Pure hadronic processes:



Weak process



Strong process

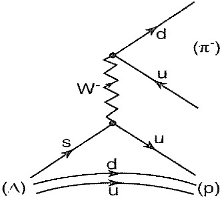
Note: Same process can also occur by strong interaction (mediator=gluon)!!

Violation of strangeness ($\Delta S = \pm 1$); GIM mechanism:

There are flavor changing weak processes involving quarks with the same color charge by different flavor ($q^{-1/3} \to W^- + q^{2/3}$) with q in the same generation

but

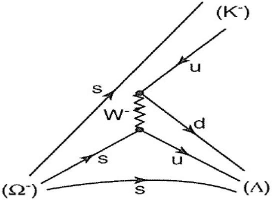
$$\Lambda(uds) \to p(udu) + \pi^-(d\bar{u}) \qquad [s \to u + W^-] \qquad \Delta S = 1$$



Lecture 14

Another flavor changing weak process with $\Delta S = 1$,

$$\Omega^-(sss) \to \Lambda^0(uds) + K^-(s\bar{u})$$



Suggestion (Cabibbo 1963)+ Glashow, Illiopoulos and Maiani (GIM) (1970), Cabibbo, Kobayashi and Maskawa (CKM) (1973)

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \to \begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$$

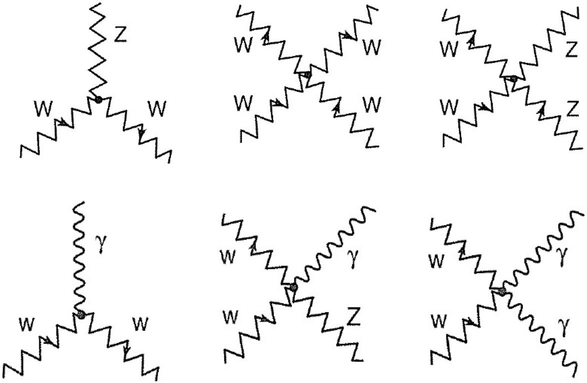
CKM-Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- $(d' \; s' \; b')$ are linear combinations of physical $(d \; s \; b)$
- If the CKM was a unit marix, no cross generational transition could occur
- V_{us} measures the coupling of u and s, etc.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.974 & 0.227 & 0.004 \\ 0.227 & 0.973 & 0.042 \\ 0.008 & 0.042 & 0.999 \end{pmatrix}$$

Self-couplings of $W^{\pm}$ and Z^0 and coupling to photon



Decays, mean lifetimes, branching ratios and conservation laws

Decay; General rule

Every particle decays into lighter particles, unless prevented from doing so by some conservation law

Stable particles:

- **Photon:** Photon has zero mass. It does not decay because of conservation of energy
- **Electron** (positron): Electron is the lightest charged particle. It does not decay because of conservation of electric charge
- **Proton** (antiproton): Proton is the lightest baryon. It does not decay because of conservation of baryon number
- **Neutrino** (antineutrino): It does not decay because of conservation of lepton flavor number

Lecture 14

Half-lifetime; Mean lifetime; Decay constant

An exponential decay process can be described by any of the following three equivalent formulae:

$$\begin{aligned} N(t) &= N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}, \\ N(t) &= N_0 e^{-\frac{t}{\tau}}, \\ N(t) &= N_0 e^{-\lambda t}, \end{aligned}$$

N_0 is the initial quantity of the substance that will decay
$N(t)$ is the quantity that still remains and has not yet decayed after a time t

Definitions:

- $t_{1/2}$ is the **half-life** of the decaying quantity
- τ is a positive number called the **mean lifetime** of the decaying quantity
- λ is a positive number called the **decay constant** of the decaying quantity

$$t_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2$$

Remark:

- **Mean lifetime (typical time of interaction):**
  - Particles which mainly decay through strong interactions have a mean lifetime of about 10^{-23} sec
  - Particles which mainly decay through electromagnetic interactions, signaled by the production of photons, have a mean lifetime in the range of $10^{-20} - 10^{-16}$ sec
  - Particles that decay through weak forces have a mean lifetime in the range of $10^{-10} - 10^{-8}$ sec

But, the lifetime depend also on the mass difference between the original and the decay products

Example: In β-decay $n \to p + e^{-} + \bar{\nu}_e$: Δm is not too large and therefore the mean lifetime of neutron $\approx$ 14 min (881 sec)

Lecture 14

Remark:

- **Mean lifetime (typical time of interaction):**
  - Particles which mainly decay through strong interactions have a mean lifetime of about 10^{-23} sec
  - Particles which mainly decay through electromagnetic interactions, signaled by the production of photons, have a mean lifetime in the range of $10^{-20} - 10^{-16}$ sec
  - Particles that decay through weak forces have a mean lifetime in the range of $10^{-10} - 10^{-8}$ sec

But, the lifetime depend also on the mass difference between the original and the decay products

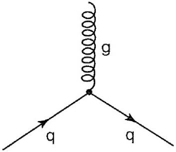
Example: In β-decay $n \rightarrow p + e^- + \bar{\nu}_e$: Δm is not too large and therefore the mean lifetime of neutron $\approx$ 14 min (881 sec)

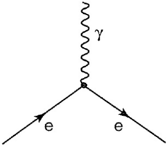
Branching ratio

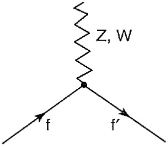
$$\begin{array}{lcll} K^+ & \rightarrow & \mu^+ + \nu_\mu, & 63\% \\ K^+ & \rightarrow & \pi^+ + \pi^0, & 21\% \\ K^+ & \rightarrow & \pi^+ + \pi^+ + \pi^-, & 6\% \\ K^+ & \rightarrow & e^+ + \nu_e + \pi^0, & 5\% \end{array}$$

Conservation laws

- **Kinematic conservation laws:** e.g. Energy-momentum conservation
- **Dynamical conservation laws:** They follow from the structure of vertices f-f-gauge with $f \in \{$leptons, quarks$\}$ and gauge $\in \{\gamma, Z^0, W^{\pm}\}$
  - Electric charge conservation
  - Color charge conservation
  - Baryon number conservation = Quark number conservation
  - Lepton number conservation
    Except: In charged weak interactions, incoming and outgoing leptons can be different
  - Quark-flavor conservation
    Except 1: Flavor changing weak processes with $\Delta S = 0$
    Except 2: Flavor changing weak processes with $\Delta S = \pm 1$ (through **GIM mechanism**)







Question: Can we guess the end products of a decay process?

$\Lambda^0(uds)$ decay $\Delta S = 0$:

$$\begin{array}{llll@{\qquad\qquad}llll}
\Lambda^0 & (uds) & \rightarrow & n \text{ or } p + ??? & S: & -1 & \rightarrow & 0 + ???\\
\Lambda^0 & (uds) & \rightarrow & n\,(udd) + K^0\ (s\bar{d}) & S: & -1 & \rightarrow & 0\ +\ -1\\
\Lambda^0 & (uds) & \rightarrow & p\,(uud) + K^-\ (s\bar{u}) & S: & -1 & \rightarrow & 0\ +\ -1
\end{array}$$

Question: Can we guess the end products of a decay process?

$\Lambda^0(uds)$ decay $\Delta S = 0$:

$$\begin{array}{llll} \Lambda^0 & (uds) & \rightarrow & n \text{ or } p + ??? \\ \Lambda^0 & (uds) & \rightarrow & n\,(udd) + K^0\ (s\bar{d}) \\ \Lambda^0 & (uds) & \rightarrow & p\,(uud) + K^-\ (s\bar{u}) \end{array} \qquad \begin{array}{lllll} S: & -1 & \rightarrow & 0 + ??? \\ S: & -1 & \rightarrow & 0\ +\ -1 \\ S: & -1 & \rightarrow & 0\ +\ -1 \end{array}$$

The problem: The above processes are kinematically not allowed

$m_{p/n} + m_K \sim (930 + 490)$ MeV $= 1420$ MeV $\gg m_{\Lambda^0} = 1116$ MeV

Correct decay products $\Delta S = 1$:

$$\begin{array}{lllll} \Lambda^0\ (uds) & \rightarrow & p\,(uud) + \pi^-\ (d\bar{u}) & & 64\% \\ \Lambda^0\ (uds) & \rightarrow & n\,(udd) + \pi^0\ (u\bar{u}) & & 36\% \end{array}$$

Another important rule: OZI rule

OZI = Okubo-Zweig-Iizuka

The problem:

$$\begin{array}{lllll} (a) & \Phi\ (s\bar{s}) & \rightarrow & K^{-}\ (s\bar{u}) + K^{+}\ (u\bar{s}) \\ (b) & \Phi\ (s\bar{s}) & \rightarrow & \pi^{0}(d\bar{d}) + \pi^{+}(u\bar{d}) + \pi^{-}(d\bar{u}) \end{array}$$

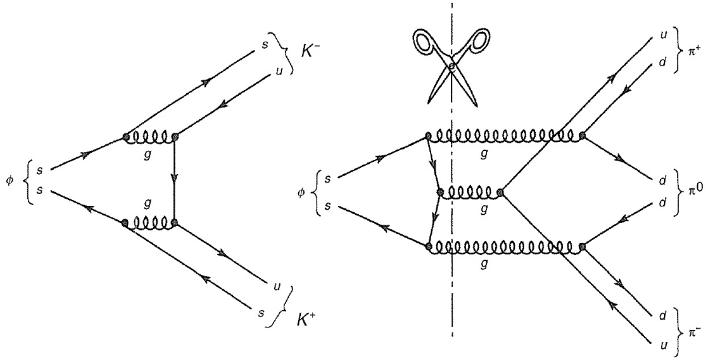
Although (b) seems to be energetically more favorable, because:

$$\Delta m_a \gg \Delta m_b$$

but (a) i favored

Question: Why?

a) $\Phi \rightarrow 2K$ **[OZI allowed]** *b*) $\Phi \rightarrow 3\pi$ **[OZI suppressed]**



The OZI rule: If the diagram can be cut in two by snipping only gluon lines (and not cutting any external legs), the process is suppressed

- In (a) gluons are soft (low energy) → strongly coupled
- In (b) gluons are hard (high energy) $[g \rightarrow q + \bar{q}] \rightarrow$ weakly coupled

** OZI= S. Okubi, Zweig, Iizuka (1960)