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# STUDY OF WEAK INTERACTIONS THROUGH FEYNMAN DIAGRAMS

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**ABOUT ARTICLE**

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**Abstract:** In the study of the properties of micro-particles in nuclear and elementary particle physics, the theory known as the Standard Model is used. According to the Standard Model, the fundamental constituents of the universe are quarks, leptons, and intermediate bosons. These elementary particles participate in four types of interactions: strong, electromagnetic, weak, and gravitational. Each interaction involves specific elementary particles and intermediate bosons that mediate the interactions. The particles participating in weak interactions are charged with what is called the weak charge – these include quarks and leptons. The mediators of weak interactions are the $W^{\pm}$ and Z massive intermediate bosons. The weak interaction is represented in a diagram using Feynman diagrams.

## INTRODUCTION

Particles involved in weak interactions possess what is referred to as weak charge, and these include quarks and leptons. The mediators of these interactions are the massive intermediate bosons $W^{\pm}$ and Z. Elementary particles with a lifetime greater than $t > 10^{-13}$ seconds decay due to weak interactions. Examples of such particles include muons and tau leptons, mesons, baryons (with lifetimes between $10^{-6}$ and $10^{-13}$ seconds), and neutrons, which all decay as a result of weak interactions. The decay of elementary particles is represented through diagrams known as Feynman diagrams.[1]

Feynman diagrams are a universal graphical method used to describe the development of elementary particle interactions over time, from the perspective of their fundamental interactions. These diagrams are accompanied by algorithms to calculate the probabilities of these processes. The time axis in Feynman diagrams is assumed to be directed from left to right. [2] Thus, particles present at the beginning of the process are placed on the left side, and the resulting particle set is shown on the right. Fermions are represented by continuous lines with arrows indicating the direction of the particle or antiparticle. The fermion line (flow) must remain continuous throughout the diagram.

## MATERIALS AND METHODS

In the Standard Model, all fundamental fermions are capable of emitting or absorbing only one type of interaction mediator during a single process. Indeed, certain fundamental fermions emit and absorb intermediate bosons, which correspond to strong, weak, and electromagnetic interactions. To illustrate these processes in diagrams, specific vertices are introduced, where the elementary interactions occur (Figure 1).[3]

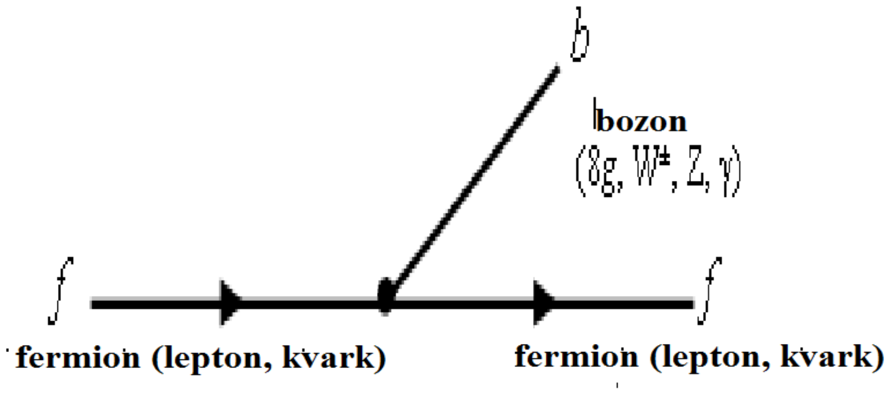


***Figure 1. Fundamental vertex describing the corresponding interaction in quantum theory (elementary node of a Feynman diagram).***

Weak interactions are mediated through the $W^{\pm}$ and Z bosons. The W± bosons have an electric charge Q = ±1e, spin I = 1, and a mass of 80.385 ± 0.015 GeV. The W+ bosons decay through the following decay channels:

$$W^{+} \rightarrow e^{+}\nu_{e}\ (10.71 \pm 0.16)\%$$

$$W^{+} \rightarrow \mu^{+}\nu_{\mu}\ (10.63 \pm 0.15)\%$$

$$W^{+} \rightarrow \tau^{+}\nu_{\tau}\ (11.38 \pm 0.21)\%$$

$W^+ \rightarrow$ adrons (67.41 ± 0.27)%

The $W^-$ boson decays similarly to the $W^+$ boson, but it only decays through channels that involve negatively charged particles.[4,5]

**Table 1: Intermediate bosons mediating weak interactions**

| Weak Interaction | W± Bosons | Z Boson |
|---|---|---|
| **Electric Charge (Q)** | ±1e | 0 |
| **Spin (I)** | 1 | 1 |
| **Mass ($m_x^2$)** | 80.385 ± 0.015 GeV | 91.1876 ± 0.0021 GeV |
| **Total Width (Γ)** | 2.085 ± 0.042 GeV | 2.4952 ± 0.0023 GeV |

The $Z^0$ boson has an electric charge of Q = 0, a spin of I = 1, and a mass of $m_Z c^2$=91.1876 ± 0.0021 GeV. $Z^0$ bosons decay through the following decay channels:

$Z \rightarrow e^+e^-$ (3.363 ± 0.004)%

$Z \rightarrow \mu^+\mu^-$ (3.366 ± 0.007)%

$Z \rightarrow \tau^+\tau^-$ (3.370 ± 0,008)%

$Z \rightarrow$ invisible (20.00 ± 0.06)%

$Z \rightarrow$ adrons (69.91 ± 0.06)%

The probability amplitude of a process is proportional to the square of the modulus $A^2$, and is determined by several factors. First, it depends on the value of the interaction constant, as each vertex contributes a factor of α. Second, it is influenced by the degree of virtuality of the mediator particle, meaning that the relation $E^2 = p^2c^2 + m^2c^4$ governs the level of deviation from the on-shell condition. The reaction energy also plays a significant role: the more energetically favorable the reaction, the higher its probability.[6,8]

## RESULT AND DISCUSSION

Among elementary particles, the neutron is one of the longer-lived particles. The half-life of a neutron is $t_{1/2}$ = 1000 seconds. Neutrons decay due to weak interactions. In weak interaction processes, the analysis of the conservation laws during neutron decay can be seen in **Table 2**:[7,13]

| | $n \rightarrow p + e^- + \bar{\nu}_e$ | |
|---|---|---|
| Q: | 0 = 1 - 1 + 0 | ΔQ = 0 |
| B: | 1 = 1 + 0 + 0 | ΔB = 0 |
| I: | $\overrightarrow{1/2} = \overrightarrow{1/2} + 0 + 0$ | $\Delta\vec{I} = 0, \vec{1}$ |
| $I_3$: | -1/2 = +1/2 + 0 + 0 | $\Delta I_3$= 1 |
| $L_e$ | 0 = 0 + 1 – 1 | $\Delta L_e$= 0 |

In neutron decay due to weak interactions, the isospin vector and its projection $I_3$ are not conserved. If we calculate the decay energy ($m_pc^2$ = 938.27 MeV, $m_ec^2$ = 0.511 MeV, and assuming the neutrino has no mass), we have:

$$Q = m_nc^2 - (m_p + m_e)c^2 = 0.782 \text{ MeV} > 0.$$

Since the reaction energy is greater than zero, the decay is allowed. The Feynman diagram of neutron decay can be seen in **Figure 1**.[9,11]

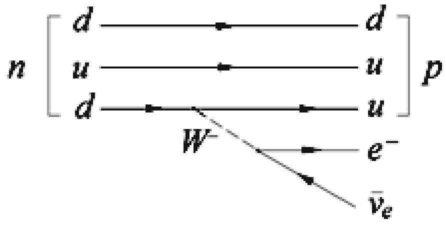


**Figure 1:** Feynman diagram of neutron decay.

Elementary particles with a lifetime greater than $t>10^{-6}$ seconds, such as the μ-leptons, also decay due to weak interactions. The μ-leptons exist in two forms, with positive and negative charges. The analysis of the conservation laws during the decay of μ-leptons can be seen in **Table 3**.[14]

| | | |
|---|---|---|
| | $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ | |
| Q: | 1 = 1 - 0 + 0 | ΔQ = 0 |
| B: | 0 = 0 + 0 + 0 | ΔB = 0 |
| $L_e$ | 0 = 1 - 1+ 0 | $\Delta L_e$= 0 |
| $L_\mu$ | 0 = 0 + 1 – 1 | $\Delta L_\mu$ = 0 |
| $I_3$: | -1/2 = +1/2 + 0 + 0 | $\Delta I_3$= 1 |

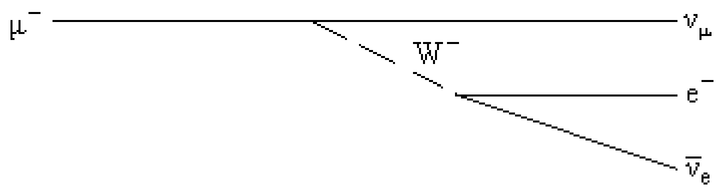


**Figure 2:** Feynman diagram of muon decay.

Heavy elementary particles, such as Λ-hyperons, with a lifetime $t>10^{-10}$ seconds, also decay due to weak interactions. The analysis of the conservation laws during the decay of Λ-hyperons can be seen in **Table 4**.

| | | |
|---|---|---|
| | $\Lambda \to p + \pi^-$ | |
| Q: | 0 = 1 −1 | ΔQ = 0 |
| B: | 1 = 1 + 0 | ΔB = 0 |
| $L_e$ | 0 = 0+ 0 | $\Delta L_e$= 0 |
| $L_\mu$ | 0 = 0 + 0 | $\Delta L_\mu$ = 0 |
| $I_3$: | 0 = +1/2 -1 | $\Delta I_3$= -1/2 |

We can see the Feynman diagram of the Λ-hyperon decay in Figure 3:

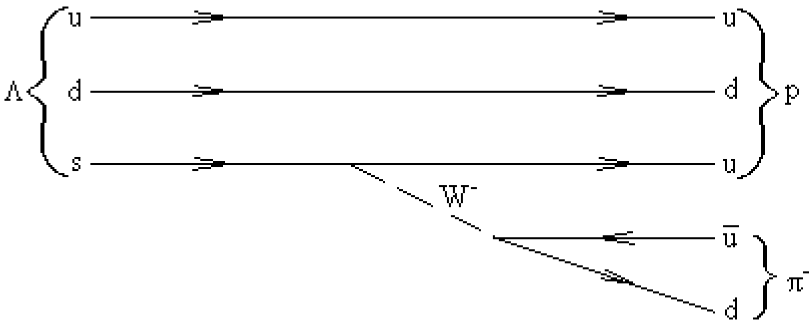


Figure 3. Feynman diagram of Λ-hyperon decay.

The decay of the Λ-hyperon can be seen from the Feynman diagram, indicating that this decay occurs as a result of the weak interaction. As a result of the Λ-hyperon decay, a proton (p) and a pi-minus meson (π−) are produced. The proton is a stable elementary particle, while the π− meson also decays through the weak interaction within $10^{-8}$ seconds.[15]

**CONCLUSION**

The creation of elementary particles primarily occurs at high energies during nuclear interactions, that is, in the process of strong interactions. The created elementary particles decay through strong interactions, electromagnetic interactions, and weak interactions.

The description of fundamental interactions through Feynman diagrams involves identifying the interaction mediator (boson) specific to each interaction. Elementary particles with lifetimes ranging from $10^{-6}$-$10^{-13}$ seconds decay due to weak interactions. Feynman diagrams provide the most convenient method to explain the decay processes of such particles.

By using Feynman diagrams, we can distinguish how a process proceeds via specific interactions and explain these processes through visual representations. Weak interactions are mediated by $W^{\pm}$ and Z bosons. As a result of weak interactions, hadrons (such as neutrons, hyperons, and mesons like pions and kaons) decay. These decays produce lighter elementary particles.

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