

## CAPÍTULO VI : INTERAÇÕES FRACAS E ELECTROFRACAS

Exemplos de decaimentos fracos :

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \tau = 2.6 \times 10^{-8} \text{ s}$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad \tau = 2.2 \times 10^{-6} \text{ s}$$

Conservação dos números quânticos  $L_e, L_\mu, L_\tau$

$\mu \rightarrow e \gamma$  : o decaimento electromagnético do múon é interdito

$$\begin{aligned} L_e = +1 & : e^- \text{ e } \bar{\nu}_e & (\text{equivalentes para } L_\mu \text{ e } L_\tau) \\ L_e = -1 & : e^+ \text{ e } \nu_e \\ L_e = 0 & : \text{todas as outras} \\ & \text{partículas} \end{aligned}$$

Outros decaimentos fracos :

$$\begin{aligned} K^+ &\rightarrow \mu^+ \nu_\mu, e^+ \nu_e \\ K^+ &\rightarrow \pi^0 \mu^+ \nu_\mu, \pi^0 e^+ \nu_e \end{aligned} \left. \vphantom{\begin{aligned} K^+ &\rightarrow \mu^+ \nu_\mu, e^+ \nu_e \\ K^+ &\rightarrow \pi^0 \mu^+ \nu_\mu, \pi^0 e^+ \nu_e \end{aligned}} \right\} \text{semi-leptônicos}$$
$$K^+ \rightarrow \pi^+ \pi^0, \pi^+ \pi^+ \pi^-, \pi^+ \pi^0 \pi^0 \quad \text{não leptônicos}$$

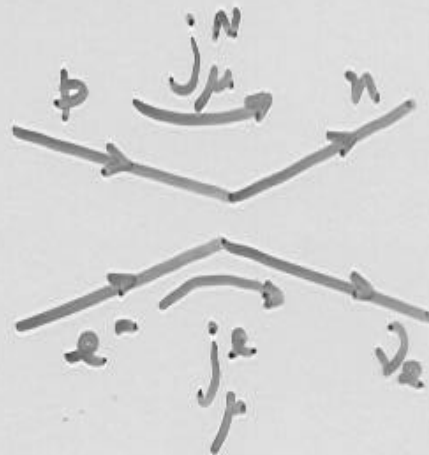
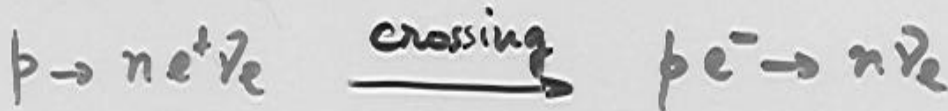
Decaimento  $\beta$  dos núcleos :

$${}^A_Z O \rightarrow {}^A_{Z-1} N + e^+ + \nu_e \quad (p \rightarrow n e^+ \nu_e)$$

$$\text{Neutrão livre : } n \rightarrow p e^- \bar{\nu}_e$$

# Violação da paridade e corrente fraca V-A

Decaimento  $\beta$  (Fermi 1932):



$$M = G \underbrace{(\bar{u}_n \gamma^\mu u_p)}_{j_\mu^N} (\bar{u}_e \gamma_\mu u_\nu)$$

(corrente carregadas)

por analogia com a difusão electromagnética  $e^- p \rightarrow e^- p$ :  
(próton considerado pontual)

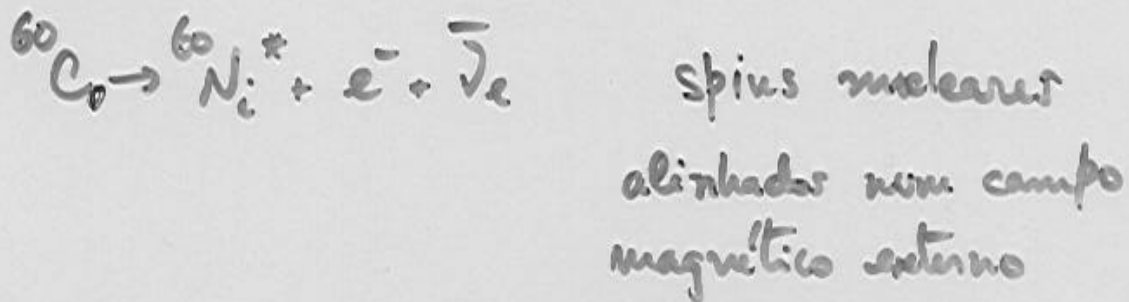


$$M = (e \bar{u}_p \gamma^\mu u_p) \left( \frac{-1}{q^2} \right) (-e \bar{u}_e \gamma_\mu u_e)$$

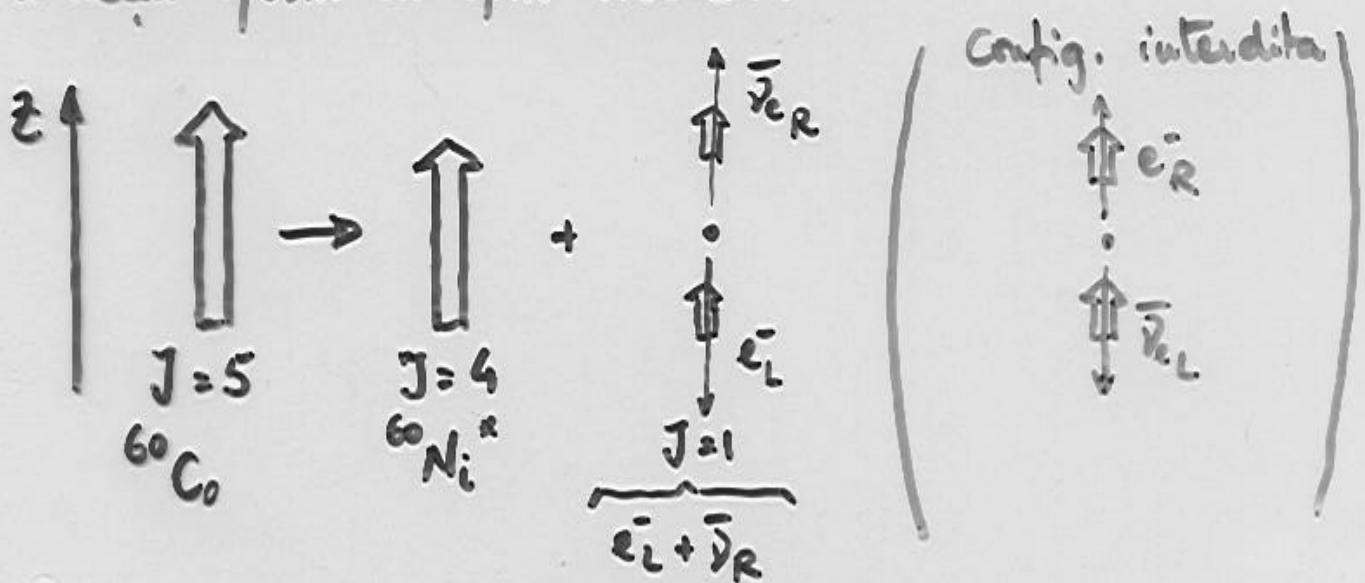
↓  
propagador do fóton

# Vidação da paridade nas interacções fracas:

EXPERIÊNCIA:



Os electrões são emitidos preferencialmente na  
 direcção oposta ao spin nuclear



Só os estados  $\nu_L$  e  $\bar{\nu}_R$  participam nas  
interacções fracas

Violação de conjugação de carga (C) :  
(partícula  $\rightarrow$  antipartícula)

$$\nu_L \rightarrow \bar{\nu}_L$$

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^+ \rightarrow \mu^+ \nu_R) \text{ so violação de P}$$

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_L) \text{ so violação de C}$$

mas :

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) = \Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_R) \text{ invariância CP}$$

(nota: existem situações em que a simetria CP é violada)

## Corrente V-A (vector-axial vector)

$$\bar{u}_e \gamma^\mu \underbrace{\frac{1}{2}(1-\gamma^5)}_{\text{selecciona neutrino-L (ou antineutrino-R)}} u_\nu$$

selecciona neutrino-L (ou antineutrino-R)

Decaimento  $\mu$ :

$$\mathcal{M}(\mu \rightarrow \nu_e e^+ \nu_\mu) = \frac{G}{\sqrt{2}} [\bar{u}_{\nu_\mu} \gamma^\mu (1-\gamma^5) u_\mu] [\bar{u}_{\nu_e} \gamma_\mu (1-\gamma^5) u_e]$$

Decaimento do múon:  $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

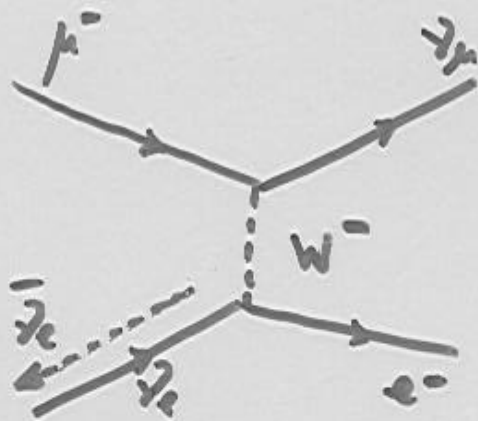


$$\mathcal{M} = \frac{G}{\sqrt{2}} [\bar{u}_{\nu_\mu} \gamma^\mu (1-\gamma^5) u_\mu] [\bar{u}_e \gamma_\mu (1-\gamma^5) u_{\nu_e}]$$

Forma geral das amplitudes:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} J^\mu J_\mu^\dagger$$

## Bosões fracos $W^\pm$ e constante $G$ :



$$\eta = \left[ \frac{g}{\sqrt{2}} \bar{u}_\nu \gamma^\sigma \frac{1}{2} (1 - \gamma^5) u_\mu \right] \underbrace{\frac{1}{M_W^2 - q^2}}_{\text{propagação do bóson } W} \left[ \frac{g}{\sqrt{2}} \bar{u}_e \gamma^\sigma \frac{1}{2} (1 - \gamma^5) u_\nu \right]$$

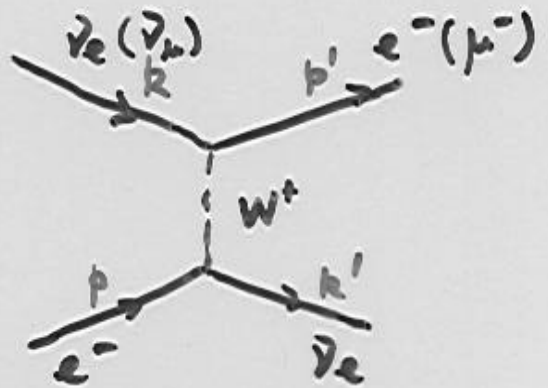
$$\text{se } q^2 \ll M_W^2 : \quad \frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \quad G \approx 10^{-5} / m_H^2$$

# Difusão eletrão - neutrino (corrente carregada)

NEUTRINO:

Amplitude invariante:  $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$

$$\mathcal{M} = \frac{G}{\sqrt{2}} [\bar{u}(k') \gamma^\mu (1-\gamma^5) u(p)] \times [\bar{u}(p') \gamma_\mu (1-\gamma^5) u(k)]$$

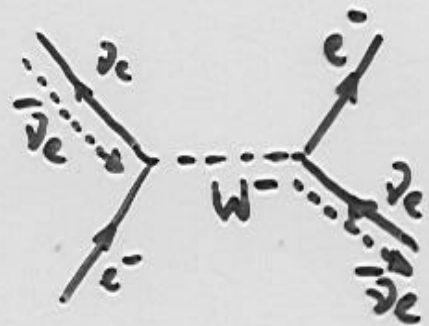


$$\frac{d\sigma(\bar{\nu}_e e^-)}{d\Omega} = \frac{G^2 s}{4\pi^2}$$

$$s = (k+p)^2$$

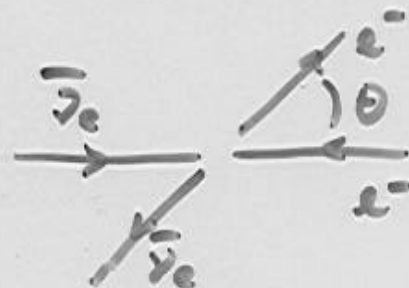
$$\sigma(\bar{\nu}_e e^-) = \frac{G^2 s}{\pi}$$

ANTI-NEUTRINO:  $\bar{\nu}_e e^- \rightarrow e^- \bar{\nu}_e$

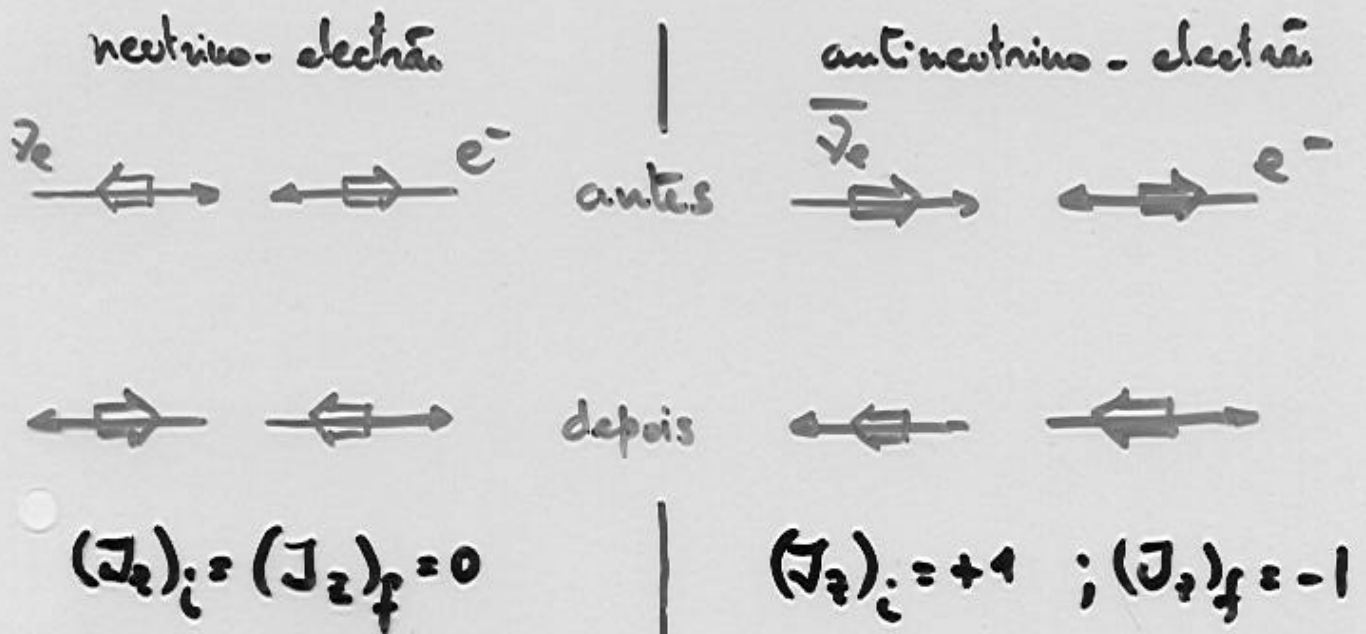


$$\frac{d\sigma(\bar{\nu}_e e^-)}{d\Omega} = \frac{G^2 s}{16\pi^2} (1 - \cos\theta)^2$$

$$\sigma(\bar{\nu}_e e^-) = \frac{G^2 s}{3\pi}$$



# Retrodifusão ( $\cos \theta = 1$ ):



Permitido

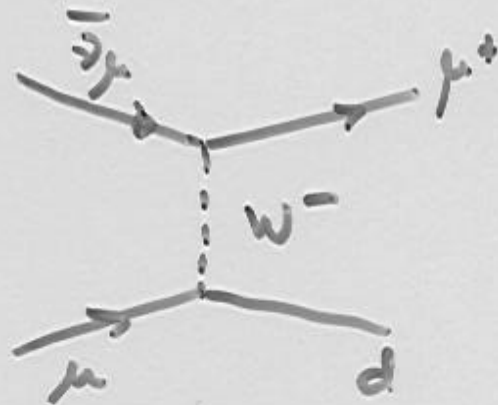
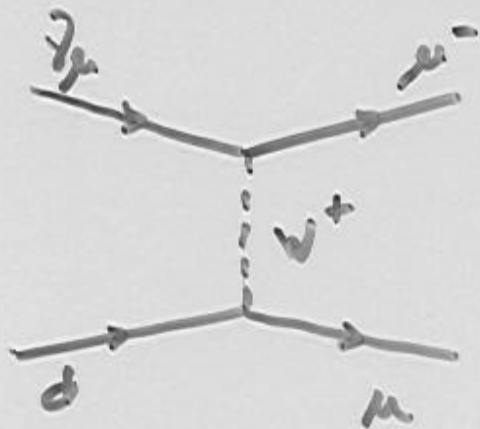
$$\frac{d\sigma}{d\Omega} = \frac{G^2 s}{4\pi^2}$$

Intendito

$$\frac{d\sigma}{d\Omega} = \frac{G^2 s}{16\pi^2} (1 - \cos \theta)^2$$



## Difusão neutrino-quark :



$$J_q^\mu = \bar{u}_\mu \gamma^\mu (1 - \gamma^5) u_d$$

$$\frac{d\sigma}{d\Omega} (\bar{\nu}_\mu d \rightarrow \mu^- u) = \frac{G^2 s}{4\pi^2}$$

$$\frac{d\sigma}{d\Omega} (\bar{\nu}_\mu u \rightarrow \mu^+ d) = \frac{G^2 s}{16\pi^2} (1 + \cos\theta)^2$$

Difusão neutrino-nucleão  $\rightarrow$

$\rightarrow$  convolução com as funções de estrutura

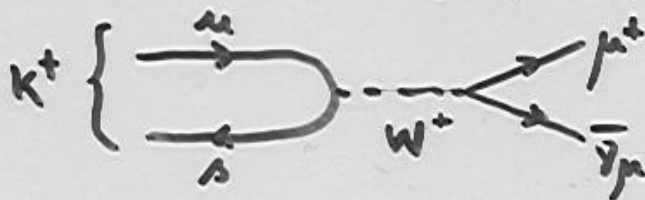
## Ângulo de Cabibbo :

Viv-se que as correntes carregadas (V-A) são formadas a partir dos doublets :

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} ;$$

pretende-se estender o esquema ao doublet  $\begin{pmatrix} c \\ s \end{pmatrix}$ .

Mas o decaimento  $K^+ \rightarrow \mu^+ \bar{\nu}_\mu$  implica corrente  $u \leftrightarrow s$  :



A interação neutra acopla combinação lineares dos estados de massa :

$$\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \dots$$

com

$$d' = d \cos \theta_c + s \sin \theta_c$$

$$s' = -d \sin \theta_c + s \cos \theta_c$$

$\theta_c$  ângulo de Cabibbo

Determinação experimental de  $\theta_c \rightarrow$  comparação de decaimentos  $\Delta S=0$  e  $\Delta S=1$  :

$$\frac{\Gamma(K^+ \rightarrow \mu^+ \bar{\nu}_\mu)}{\Gamma(\pi^+ \rightarrow \mu^+ \bar{\nu}_\mu)} \sim \frac{\sin^2 \theta_c}{\cos^2 \theta_c}$$

$$\Delta S=1 : K^+ \rightarrow \mu^+ \bar{\nu}_\mu : u \leftrightarrow s$$

$$\Delta S=0 : \pi^+ \rightarrow \mu^+ \bar{\nu}_\mu : u \leftrightarrow u$$

$$\rightarrow \theta_c \approx 13^\circ$$

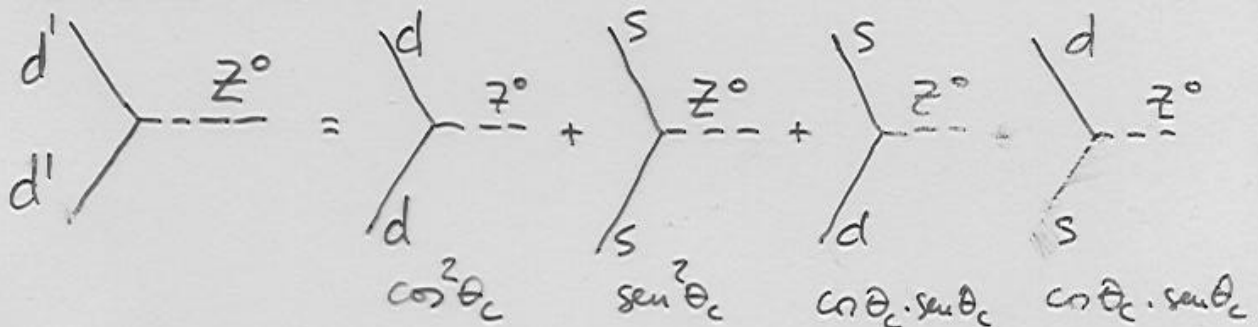
# QUARK CHARM : MECANISMO DE GIM

1) Angulo de Cabibbo :

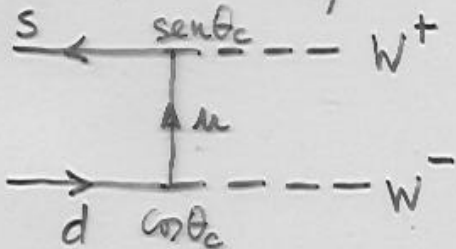
$$\Rightarrow d' = d \cdot \cos \theta_c + s \cdot \sin \theta_c$$

$$\Rightarrow \text{doblete } \begin{pmatrix} u \\ d' \end{pmatrix}$$

2) Implic:  
correntes neutras:



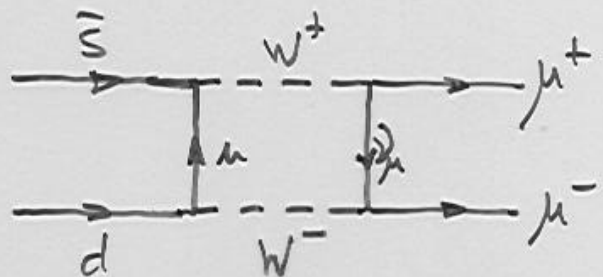
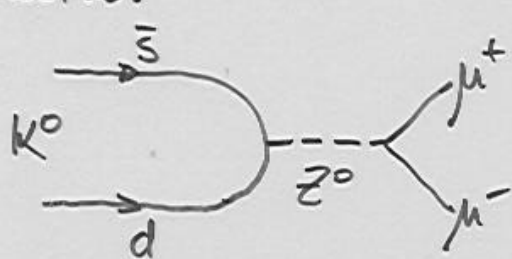
correntes carregadas :



3) Contradição com observação experimental :

$$\text{Decaimento do } K^0 (d\bar{s}) : BR^{exp}(K^0 \rightarrow \mu^+ \mu^-) < 9 \cdot 10^{-9}$$

Teoria:



4) Soluções:

Dois doubletos:  $\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} e \\ s' \end{pmatrix}$

$$d' = d \cos \theta_c + s \operatorname{sen} \theta_c$$

$$s' = -d \operatorname{sen} \theta_c + s \cos \theta_c$$

Diagramas cancelam:

