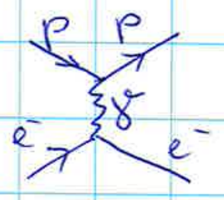
4.5. ŠIBKA INTERAKCIJA

$\tau(\pi^-) = 2.6 \cdot 10^{-8}\,s$ $\qquad$ $\tau(\pi^0) = 8.4 \cdot 10^{-17}\,s$

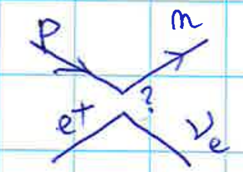
$d\bar{u}$ $\qquad \pi^- \to \mu^- \bar{\nu}_\mu$ $\qquad \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ $\quad \pi^0 \to \gamma\gamma$ EM INTERAKCIJA

FERMI 1932 : ANALOGIJA Z E.M. INTERAKCIJO



$$-i\mathcal{M} = e^2 \left[\bar{u}_p \gamma^\kappa u_p\right]\left(\frac{-g_{\kappa\nu}}{q^2}\right)\left[\bar{u}_e \gamma^\nu u_e\right]$$ E.M. INTERAKCIJA

PRIMER ŠIBKEGA PROCESA: RAZPAD BETA $\quad {}^{10}\underset{p}{C} \to {}^{10}Be\ \underset{n\,e^+\nu_e}{e^+ \nu_e}$



$$-i\mathcal{M} = \frac{G_F}{\sqrt{2}} \left[\bar{u}_n \gamma^\kappa u_p\right]\left[\bar{u}_\nu \gamma_\kappa u_e\right]$$

G_F : FERMIJEVA SKLOPITVENA KONSTANTA

1950 LETA ! "Θ^+/τ^+" UGANKA: "Θ^+" $\to \pi^+\pi^0$, "τ^+" $\to \pi^+\pi^-\pi^+$, MASA Θ^+ IN τ^+

IZKAZALO SE JE, DA $\Theta^+ = \tau^+ = K^+$ $\qquad$ PARNOST $P_{\Theta^+} = P_\pi^2 = (-1)^2 = +1$

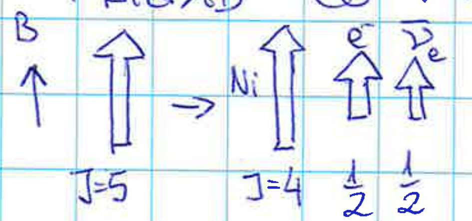
E.M. IN MOČNA INTERAKCIJA: PARNOST SE OHRANJA $\qquad P_{\tau^+} = P_\pi^3 = (-1)^3 = -1$

1956 ! T.D. LEE + CHEN-NING YANG ! ŠIBKA INTERAKCIJA NE OHRANJA PARNOSTI

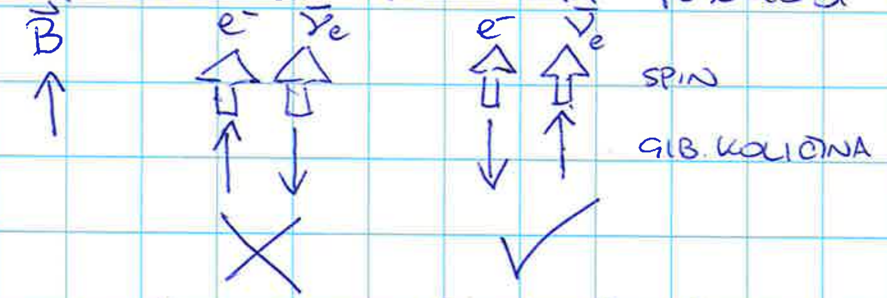
EKSPERIMENT S ${}^{60}Co$ $\quad$ CHEN SHIUNG WU $\quad$ RAZPAD ${}^{60}Co$ V MOČNEM MAGNETNEM POLJU

$${}^{60}Co \to {}^{60}Ni\ e^- \bar{\nu}_e$$

$J = 5 \qquad J = 4 \quad \frac{1}{2} \quad \frac{1}{2}$

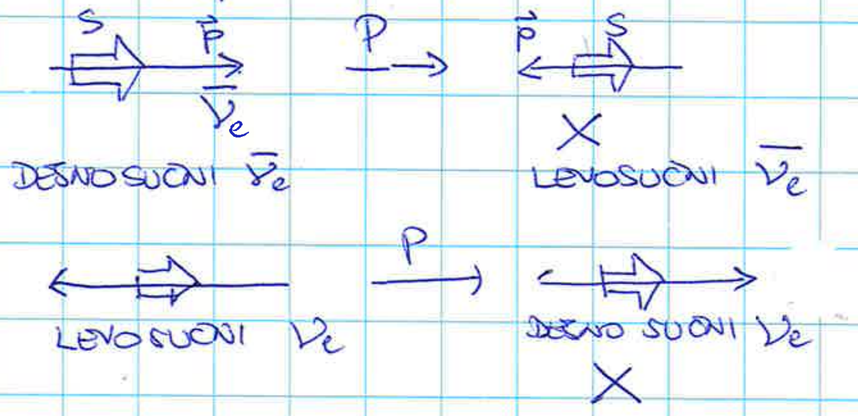


PRI POSKUSU PRIMERJAM POGOSTOST ELEKTRONOV <u>U SMERI</u> $\vec{B}$ IN <u>U NASPROTNI</u> SMERI

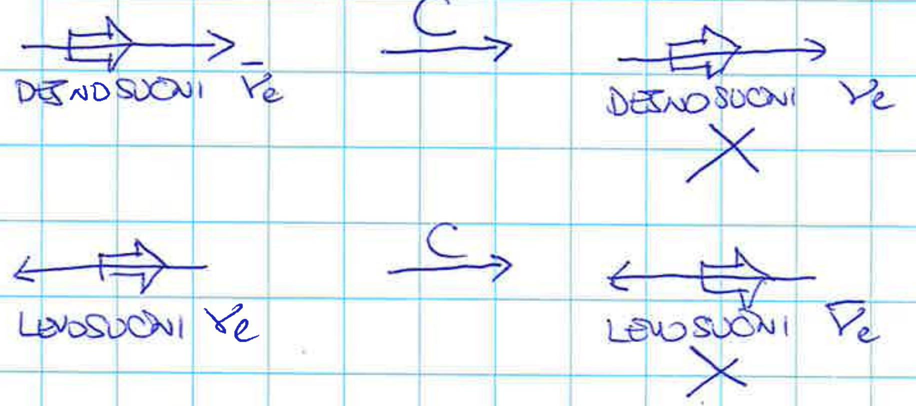


$P: \ \vec{p} \to -\vec{p} \ , \ \vec{S} \xrightarrow{P} \vec{S}$

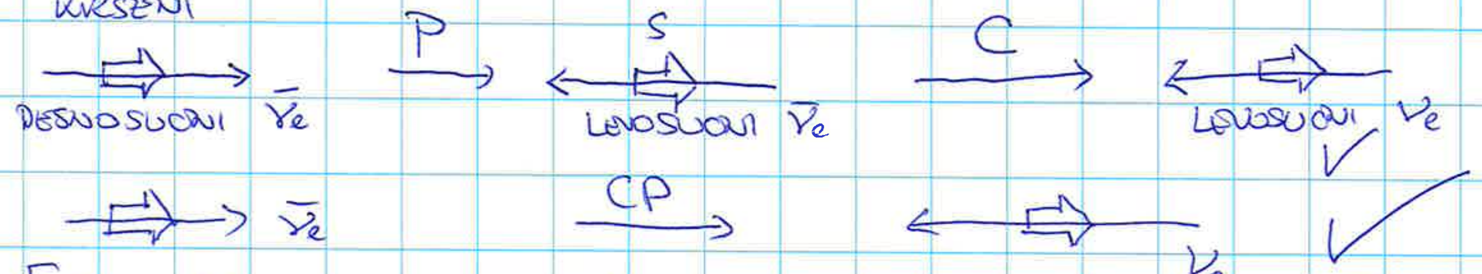
$\vec{r} \times \vec{p} \xrightarrow{P} (-\vec{r}) \times (-\vec{p}) = \vec{r} \times \vec{p}$



KRŠENA JE TUDI PARNOST C ! DELEC → ANTIDELEC



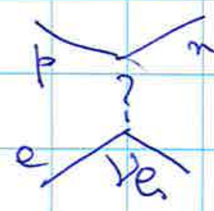
P, C KRŠENI



CP SE OHRANJA

[1964 FITCH, CRONIN, CP SE NE OHRANJA PRI RAZPADIH K^0]

KAKO NAPISAT $\mathcal{M}$, DA BO AVTOMATIČNO POSKRBEL ZA NEOHRANITEV PARNOST



$$\boxed{-i\mathcal{M} = \frac{G_F}{\sqrt{2}} \left[\bar{u}_n \gamma^k (1-\gamma^5) u_p\right]\left[\bar{u}_\nu \gamma_k (1-\gamma^5) u_e\right]}$$

$$\gamma^5 = \gamma^0\gamma^1\gamma^2\gamma^3 = \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} \qquad I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad \gamma^{5+} = \gamma^5 \,, \ (\gamma^5)^2 = I \qquad \gamma^5\gamma^\mu + \gamma^\mu\gamma^5 = 0$$

$\frac{1}{2}(1-\gamma^5)\,u = u_L$ LEVO ROČNI BISPINOR

$\frac{1}{2}(1+\gamma^5)\,u = u_R$ DESNO ROČNI BISPINOR

$$u_L + u_R = u$$

$$\gamma^5 u_L = \gamma^5 \tfrac{1}{2}(1-\gamma^5)\,u = \tfrac{1}{2}(\gamma^5 - 1)\,u = -\tfrac{1}{2}(1-\gamma^5)\,u = -u_L$$

$$\gamma^5 u_R = \gamma^5 \tfrac{1}{2}(1+\gamma^5)\,u = \tfrac{1}{2}(\gamma^5 + 1)\,u = +u_R$$

$$\left[\tfrac{1}{2}(1-\gamma^5)\right]^2 = \tfrac{1}{4}(1 - 2\gamma^5 + 1) = \tfrac{1}{4}(2 - 2\gamma^5) = \tfrac{1}{2}(1-\gamma^5)$$ PROJEKTOR

LEVO ROČNI BISPINOR $u_L = \frac{1}{2}(1-\gamma^5)\,u = \frac{N}{2}\begin{bmatrix} I & -I \\ -I & I \end{bmatrix}\begin{pmatrix} \chi \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi \end{pmatrix} = \frac{N}{2}\begin{pmatrix} \chi - \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi \\ -\chi + \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\chi \end{pmatrix}$

ZA $E \gg m$ ULTRAREL. LIMITA: $\frac{\vec{p}}{E+m} = \hat{p}$ ENOTSKI SMERNI VEKTOR $\Rightarrow u_L = \frac{N}{2}\begin{pmatrix} \chi - \vec{\sigma}\cdot\hat{p}\chi \\ -(\chi - \vec{\sigma}\cdot\hat{p}\chi) \end{pmatrix}$

SUČNOST: u_L ! OPERATOR $\vec{\Sigma}\cdot\hat{p}$

$$\vec{\Sigma}\cdot\hat{p}\, u_L = \begin{bmatrix} \vec{\sigma}\cdot\hat{p} & 0 \\ 0 & \vec{\sigma}\cdot\hat{p} \end{bmatrix} u_L = \frac{N}{2}\begin{pmatrix} \vec{\sigma}\cdot\hat{p}(\chi - \vec{\sigma}\cdot\hat{p}\chi) \\ -\vec{\sigma}\cdot\hat{p}(\chi - \vec{\sigma}\cdot\hat{p}\chi) \end{pmatrix}$$

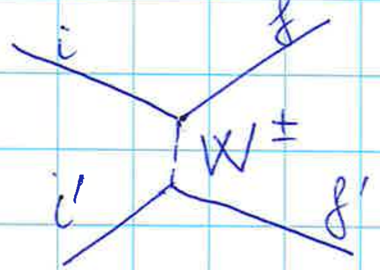
UPOŠTEVAMO $(\vec{\sigma}\cdot\hat{p})^2 = 1$

$$= \frac{N}{2}\begin{pmatrix} \vec{\sigma}\cdot\hat{p}\chi - \chi \\ -(\vec{\sigma}\cdot\hat{p}\chi - \chi) \end{pmatrix} = -u_L$$

$\Rightarrow$ V ULTRARELATIVISTIČNI LIMITI JE LEVOROČEN DELEC TUDI LEVO SUČEN

PODOBNO $\Sigma\cdot\hat{p}\, u_R = +u_R$ U ULTRARELATIVIST. LIMITI DESNO ROČEN = DESNO SUČEN

KONČNA OBLIKA MATRIČNEGA ELEMENTA ZA ŠIBEK PROCES



$$\boxed{-i\mathcal{M} = \left[\frac{g_W}{\sqrt{2}}\bar{u}_f\gamma^\mu(1-\gamma^5)u_i\right]\left(-\frac{g_{\mu\nu}}{M_W^2-q^2}\right)\left[\frac{g_W}{\sqrt{2}}\bar{u}_{f'}\gamma^\nu(1-\gamma^5)u_{i'}\right]}$$

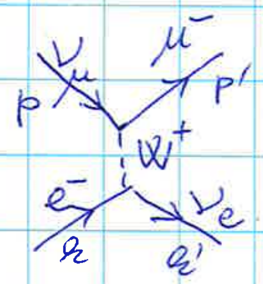
$M_W = 83$ GeV

RAZPAD β (NIZKE ENERGIJE): $q^2 \ll M_W^2$ DOBIMO IZRAZ NA DNU STRANI 52, KJER

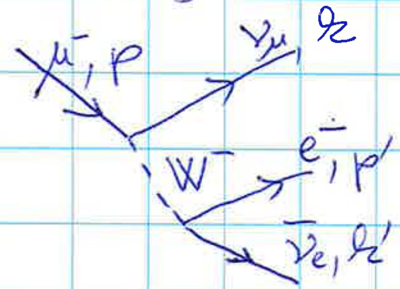
$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{2}\frac{1}{M_W^2} \Rightarrow G_F = \frac{g_W^2}{\sqrt{2}M_W^2}$$

1. PRIMER: ŠIBKEGA PROCESA $\nu_\mu e^- \to \mu^- \nu_e$

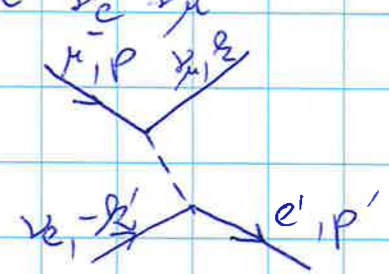
$$-i\mathcal{M} = \left[\frac{g_W}{\sqrt{2}}\bar{u}(p')\gamma^\kappa(1-\gamma^5)u(p)\right]\left(-\frac{g_{\kappa\nu}}{M_W^2-q^2}\right)\left[\frac{g_W}{\sqrt{2}}\bar{u}(q')\gamma^\nu(1-\gamma^5)u(q)\right]$$



2. PRIMER: RAZPAD MIONA $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



$\equiv$



RAZPADNA ŠIRINA

$$\Gamma = \frac{\hbar}{\tau}$$

$$d\Gamma = \frac{|\mathcal{M}|^2}{2E}\, dQ$$

FAZNI PROSTOR

$$dQ = \frac{d^3p'}{(2\pi)^3 2E'} \frac{d^3k}{(2\pi)^3 2\omega} \frac{d^3k'}{(2\pi)^3 2\omega'} (2\pi)^4 \delta^4(p-p'-k-k')$$

e^- ν_μ $\bar{\nu}_e$

RAČUNALI BOMO $\frac{d\Gamma}{dE'}$ SPEKTER ELEKTRONOV, NAJ PREJ INTEGRIRAMO PO k

PRI TEM UPOŠTEVAMO IDENTITETO $\int \frac{d^3k}{2\omega} = \int d^4k\, \Theta(\omega)\, \delta(k^2)$ $\Theta(\omega) = \begin{cases} 1, & \omega \geq 0 \\ 0, & \omega < 0 \end{cases}$

$$dQ = \frac{1}{(2\pi)^5} \cdot \frac{d^3p'}{2E'} \cdot \frac{d^3k'}{2\omega'} \int d^4k\, \Theta(\omega)\, \delta(k^2)\, \delta^4(p-p'-k-k') =$$

$$= \frac{1}{(2\pi)^5} \cdot \frac{d^3p'}{2E'} \frac{d^3k'}{2\omega'} \Theta(E-E'-\omega')\, \delta((p-p'-k')^2)$$

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

UVEDEMO BISPINOR. ZA ANTIDELEC $v(k')$ $u^{(1,2)} e^{-ipx}$ ZA $E>0$

$u^{(3,4)} e^{-(-ipx)} \equiv v^{(2,1)} e^{ipx}$; $E>0$

DIRACOVA ENAČBA ZA v: $(\not{p}+m)v=0$ | (ZA u: $(\not{p}-m)u=0$)

POLNOSTNA RELACIJA ZA v: $\sum_{s=1,2} v^{(s)}(p)\bar{v}^{(s)}(p) = \not{p}-m$ | ZA u: $\sum_{s=1,2} u^{(s)}(p)\bar{u}^{(s)}(p) = \not{p}+m$

TAKO JE $\overline{|\mathcal{M}|^2} = \frac{1}{2}\left(\frac{G_F}{\sqrt{2}}\right)^2 \sum [\bar{u}(k)\gamma^\mu(1-\gamma^5)u(p)][\bar{u}(p')\gamma_\mu(1-\gamma^5)v(k')][\bar{u}(k)\gamma^\sigma(1-\gamma^5)u(p)]^\dagger[\bar{u}(p')\gamma_\sigma(1-\gamma^5)v(k')]^\dagger$

PO VSEH SPINIH

$a^* = a^+$ ČE a KOMPLEKSNA ŠTEVILKA

$$\left[\bar{u}(k)\gamma^{\delta}(1-\gamma^5)u(p)\right]^{+} = \left[u^{+}(k)\gamma^{0}\gamma^{\delta}(1-\gamma^5)u(p)\right]^{+} = u^{+}(p)(1-\gamma^5)^{+}\gamma^{\delta +}\gamma^{0+}u(k) = u^{+}(p)(1-\gamma^5)\gamma^{\delta +}\gamma^{0}u(k) =$$

$$= + u^{+}(p)\gamma^{0}(1+\gamma^5)\gamma^{\delta}u(k) = \bar{u}(p)\gamma^{\delta}(1-\gamma^5)u(k)$$

$\gamma^{\delta +}\gamma^{0} = \gamma^{0}\gamma^{\delta}$

PODOBNO $$\left[\bar{u}(p')\gamma_{\delta}(1-\gamma^5)v(k')\right]^{+} = \bar{v}(k')\gamma_{\delta}(1-\gamma^5)u(p')$$

M.S.