M+S CHAP. 11
2019
A. READ

CHARGED WEAK INTERACTIONS AND C, P

~SAME MASSES

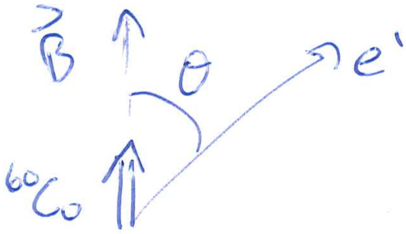
$K^+ \to \pi^+\pi^0$ $\quad P = 1$ "τ"

$K^+ \to \pi^+\pi^-\pi^+$ $\quad P = -1$ "θ"

CAN 1 PARTICLE DECAY TO DIFFERENT PARITY STATES?

LEE + YANG (1956) – NO EXPERIMENT EXPLICITLY TEST P-CONS. IN WEAK INTERACTIONS.

Wu et. al. (1957) POLARIZED $^{60}Co \to {}^{60}Ni^+ e^- \bar{\nu}_e$ IN $\vec{B}$-FIELD



$\xrightarrow{\text{PARITY}}$

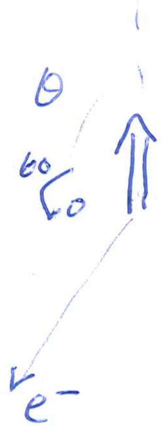
$\vec{x} \to -\vec{x}$

$\vec{p} \to -\vec{p}$

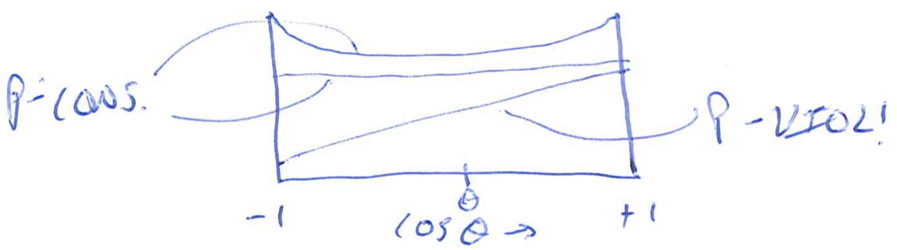
$\vec{l} = \vec{r} \times \vec{p} \to \vec{l}$

$\vec{B} \to \vec{B}$

$\vec{E} \to -\vec{E}$



PARITY CONSERVATION: $I(\theta) = I(\pi - \theta)$



EXPERIMENTAL RESULTS: $1 - \left(\frac{P v_e}{c}\right) \cos\theta$

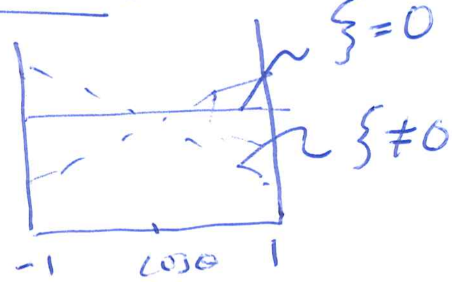
BONUS: $\frac{v}{c}\cos\theta = \beta\cos\theta = \frac{p}{E}\cos\theta = \frac{\vec{p}\cdot\vec{\sigma}}{E}$ ← UNIT SPIN VECTOR

$\vec{p}\cdot\vec{\sigma}$ IS A SCALAR BUT $P(\vec{p}\cdot\vec{\sigma}) = (-\vec{p})\cdot(\vec{\sigma})$
$= -\vec{p}\cdot\vec{\sigma}$

SCALAR THAT CHANGES SIGN UNDER PARITY IS "PSEUDOSCALAR"

CONSIDER POLARIZED $\mu^\pm$-DECAYS

$$\left.\begin{array}{l}\mu^- \to e^- \, \bar{\nu}_e \, \nu_\mu \\ \mu^+ \to e^+ \, \nu_e \, \bar{\nu}_\mu\end{array}\right\} C$$



DECAY RATE $$\frac{d\Gamma_{\mu\pm}}{d\cos\theta} = \frac{1}{2}\Gamma_\pm\left[1 - \frac{\xi_\pm}{3}\cos\theta\right]$$

$$\Gamma = \int_{-1}^{+1} \frac{d\Gamma}{d\cos\theta}\, d\cos\theta = \frac{1}{2}\Gamma_\pm \int \left(1 - \frac{\xi_\pm}{3}\cos\theta\right) d\cos\theta$$ 2-ν's

$$= \Gamma_\pm = \frac{1}{\tau_\pm}, \quad (\text{IND. OF } \xi)$$

PARITY CONS: $\xi = 0$

CHARGE CONJ. CONS: $\xi_+ = \xi_-$, $\Gamma_+ = \Gamma_-$

EXPERIMENT: $\xi \neq 0$, $\xi_- = -\xi_+ = 1$, $\Gamma_+ = \Gamma_- = \Gamma$

BOTH C AND P VIOLATED!!

WHAT ABOUT CP?

$$\frac{d\Gamma_+}{d\cos\theta} = \frac{1}{2}\Gamma_+\left(1 + \frac{1}{3}\cos\theta\right)$$

$$\downarrow P$$

$$\frac{d\Gamma_+}{d\cos\theta} = \frac{1}{2}\Gamma_+\left(1 - \frac{1}{3}\cos\theta\right)$$

$$\downarrow C$$

$$\frac{d\Gamma_-}{d\cos\theta} = \frac{1}{2}\Gamma_-\left(1 - \frac{1}{3}\cos\theta\right)$$

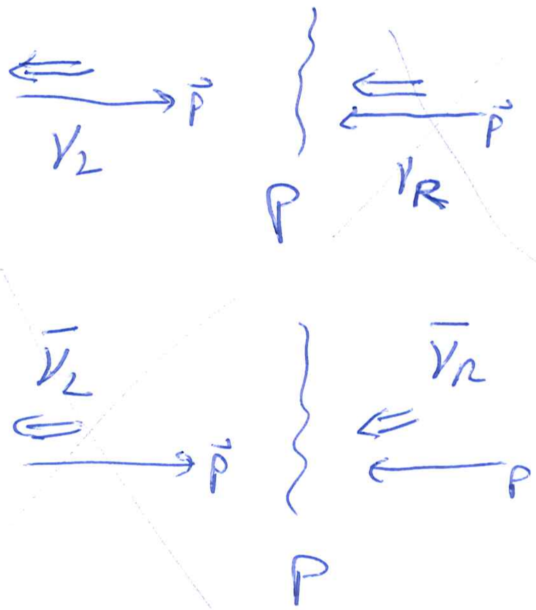
$$\frac{d\Gamma_\pm}{d\cos\theta} = \frac{1}{2}\Gamma\left(1 \pm \frac{1}{3}\cos\theta\right)$$

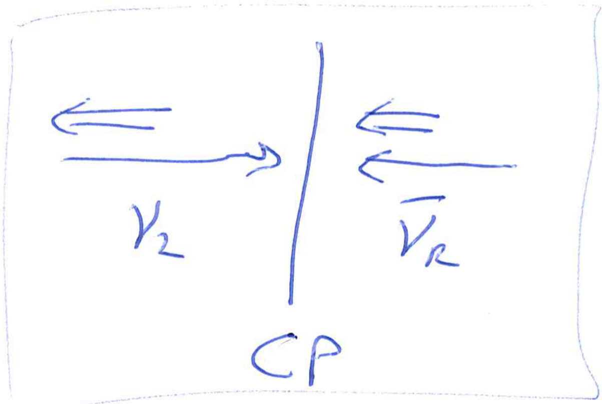
✓

CP-CONSERVED!

LEFT-HANDED NEUTRINOS

FOR MASSLESS PARTICLES NO LORENTZ-FRAME THAT CAN FLIP THE SPIN!





P-VIOL + CP-CONS

$\Rightarrow$ NO ν_R, $\bar{\nu}_L$

ONLY ν_L, $\bar{\nu}_R$

THIS IS KEY TO UNDERSTANDING WEAK CHARGED INTERACTIONS.

(PARITY VIOLATION IN WEAK NEUTRAL CURRENT AS WELL, BUT MUCH WEAKER).

ν_L, $\bar{\nu}_R$ FOR <u>MASSLESS</u> ν's

FOR MASSIVE PARTICLES SUPRESSION IS $1-\beta$

$$\left(\frac{E}{m}\right)^2 = \gamma^2 = \frac{1}{1-\beta^2} = \frac{1}{(1-\beta)(1+\beta)} \simeq \frac{1}{2(1-\beta)}$$

$$1-\beta \simeq \frac{1}{2}\left(\frac{m}{E}\right)^2$$

CONSIDER PION DECAYS

$$\pi^+ \to e^+\nu_e,\ \mu^+\nu_\mu$$

$m_e = 511$ keV

$m_\mu = 105.7$ MeV

$m_\pi = 139.6$ MeV

$$\mu^+_L \xleftarrow{\ \Rightarrow\ } \pi^+ \xrightarrow{\ \Leftarrow\ } \nu_\mu^L \qquad J=0$$

$m_\mu \lesssim m_\pi$

$\beta \ll 1$

*

REPLACE μ w/ e $\to \beta \sim 1$

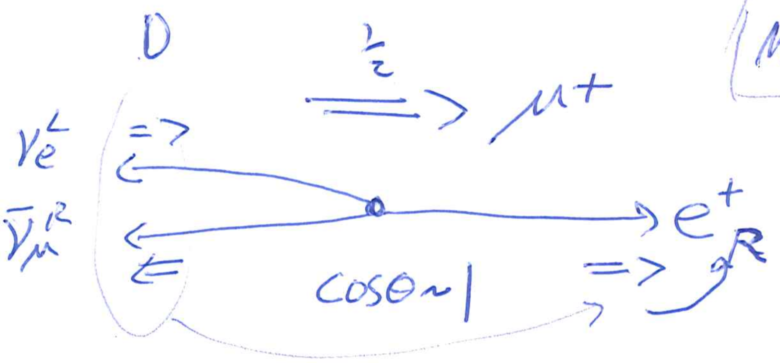
SUPRESSION $1-\beta_e \simeq \frac{1}{2}\frac{m_e^2}{(m_\pi/2)^2} \sim 3\cdot 10^{-5}$

EXPT. RESULT: $12\cdot 10^{-5} = \frac{m_e^2}{m_\mu^2}\frac{\left(1-\frac{m_e^2}{m_\pi^2}\right)^2}{\left(1-\frac{m_\mu^2}{m_\pi^2}\right)}$

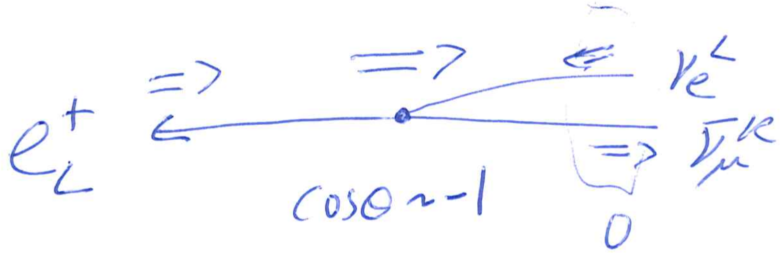
QUESTION: HOW CAN WE MAKE A BEAM OF POLARIZED MUONS STARTING FROM A PION BEAM?

CONSIDER μ - DECAYS

$\boxed{\text{MAX. } e^+\text{-ENERGY}}$

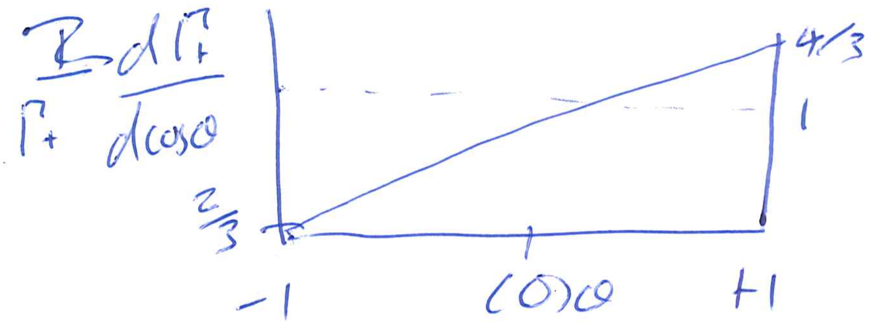


: ALLOWED



: SUPRESSED

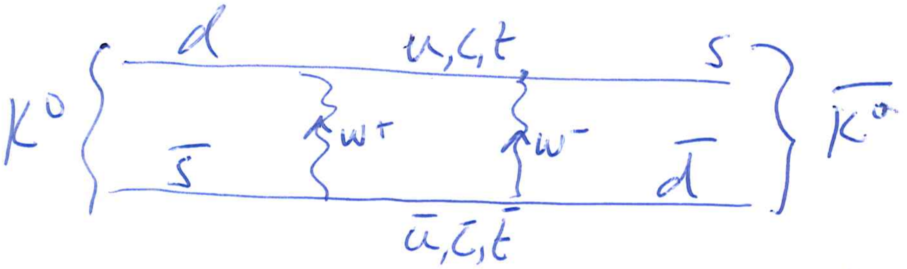
$m_e << m_\mu \to \beta_e \sim 1$



AVG. OVER e^+-ENERGIES

$$\frac{d\Gamma_+}{d\cos\theta} = \frac{1}{2}\Gamma_+\left(1+\frac{1}{3}\cos\theta\right)$$

$K^0 - \bar{K}^0$ MIXING (SIMILAR MATH FOR $D^0 - \bar{D}^0$, $B^0 - \bar{B}^0$)



+ANOTHER SIMILAR SET OF (BOX) DIAGRAMS.

$$\underbrace{S = +1 \qquad S = 0 \qquad S = -1}_{\Delta S = -2!}$$

NO ABSOLUTE EIGENSTATES OF WEAK INTERACTION.
LONG LIFETIME MEANS $K^0 \leftrightarrow \bar{K}^0$ OBSERVABLE.

- TRY ASSUMING THAT CP IS A GOOD Q. NUMBER

$$\cancel{CP|K^0\rangle = -|\bar{K}^0\rangle}$$

$$\hat{C}\,|K^0, \vec{p}\rangle = -|\bar{K}^0, \vec{p}\rangle, \quad \hat{C}\,|\bar{K}^0, \vec{p}\rangle = -|K^0, \vec{p}\rangle$$

$$\hat{P}|K^0, 0\rangle = -|K^0, 0\rangle, \quad \hat{P}|\bar{K}^0, 0\rangle \overset{\text{MINUS!}}{=} -|\bar{K}^0, 0\rangle$$

$$\hat{C}\hat{P}|K^0\rangle = |\bar{K}^0\rangle, \quad \hat{C}\hat{P}|\bar{K}^0\rangle = |K^0\rangle$$ (WORK IN C.MASS $\vec{p}=0$ BY DEFAULT)

$$\text{LET } |K^0_{1,2}\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle \pm |\bar{K}^0\rangle\right]$$

$$\hat{C}\hat{P}|K^0_1\rangle = |K^0_1\rangle, \quad \hat{C}\hat{P}|K^0_2\rangle = -|K^0_2\rangle$$

$K^0_{1,2}$ ARE THUS EIGENSTATES OF CP
$K^0, \bar{K}^0$ ARE NOT SINCE $\hat{C}|K^0\rangle = |\bar{K}^0\rangle$

((CORRECTED VERSION 6.5.2019))

2 - PION STATES

CHAP. 5
$P_\pi = -1$
$C_{\pi^0} = +1$

$J_\pi = J_K = 0$

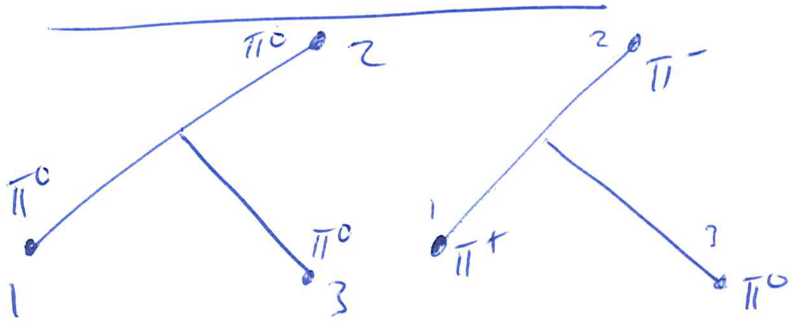
$\pi\pi$ MUST BE IN $L=0$ STATE

$C(\pi^0\pi^0) = C_{\pi^0}^2 = +1 \qquad P(\pi\pi) = P_\pi^2 (-1)^L = +1$

$C(\pi^+\pi^-) = (-1)^L = +1$

$$CP(\pi\pi) = +1$$

3 - PION STATES



$\vec{L} = \vec{L}_{12} + \vec{L}_3$

$J_{K^0} = 0 \Rightarrow L_{12} = L_3$

$C(\pi^0\pi^0\pi^0) = (C_{\pi^0})^3 = +1 \qquad P(\pi^+\pi^-\pi^0) = P_\pi^3 (-1)^{L_{12}} (-1)^{L_3}$

$C(\pi^+\pi^-\pi^0) = C_{\pi^0}(-1)^{L_{12}} \qquad = P_\pi^3 = -1$

$P(\pi^0\pi^0\pi^0) = P_\pi^3 (-1)^{L_{12}} (-1)^{L_3} = P_\pi^3 = -1$

$CP(\pi^0\pi^0\pi^0) = -1$

$CP(\pi^+\pi^-\pi^0) = C_{\pi^0}(-1)^{L_{12}} \cdot (-1) = (-1)(-1)^{L_{12}}$

ANGULAR DISTRIBUTION OF PIONS $\Rightarrow L_{12} = 0$

$$CP(\pi\pi\pi) = -1$$

OBSERVED: $K_L^0 \to \pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0, \pi^\pm \ell^\mp \bar{\nu}_\ell(\nu_\ell) \qquad \tau_L = 5 \cdot 10^{-8}\,s$

$K_S^0 \to \pi^+\pi^-, \pi^0\pi^0 \qquad$ 67%! $\qquad \tau_S = 9 \cdot 10^{-11}\,s$

$m_{K_S^0} \hat{=} m_{K_L^0} \hat{=} 498\,MeV$

CP-CONS: $\underbrace{K^0_S = K^0_1}_{CP=+1}, \underbrace{K^0_L = K^0_2}_{CP=-1}$

BUT (!!) $K^0_L \to \pi^+\pi^-$ $B \cong 10^{-3}$ (1964

CP-VIOLATION !

TYPES OF CP-VIOLATION

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1) "BY MIXING" $|K^0_S\rangle = \frac{1}{\sqrt{1+\epsilon^2}}\left(|K^0_1\rangle + \epsilon|K^0_2\rangle\right)$

$$|K^0_L\rangle = \frac{1}{\sqrt{1+\epsilon^2}}\left(\epsilon|K^0_1\rangle + |K^0_2\rangle\right)$$

"DIRECT"

2) $|K^0_L\rangle = |K^0_2\rangle$ BUT $K^0_2 \to \pi\pi$ VIOLATES CP

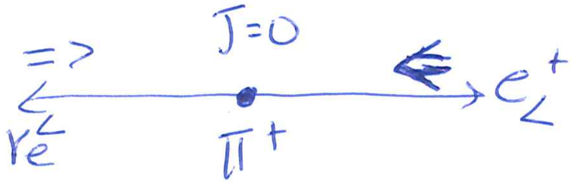
$|K^0_S\rangle = |K^0_1\rangle$ BUT $K^0_1 \to 3\pi$

EXPERIMENT: MOSTLY (1) BUT ALSO (2) !

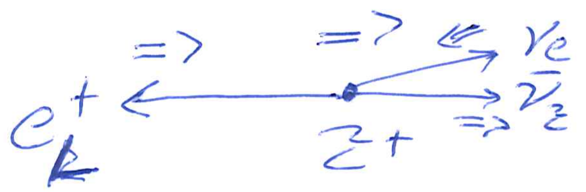
$$\frac{\Gamma(K^0_L \to e^+\pi^-\nu_e) - \Gamma(K^0_L \to e^-\pi^+\bar{\nu}_e)}{\Gamma(\quad e^+ \quad) + \Gamma(\quad e^- \quad)} = \cancel{0.33 \cdot 10} \; (0.33 \pm 0.01)\cdot 10^{-2}$$

Q

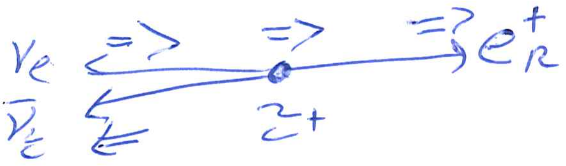
QUESTION IN BREAK: WHY THE BIG SUPRESSION IN $\pi^+ \to e^+ \nu_e$ BUT NOT IN $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$?



THIS IS THE ONLY CONFIGURATION SO SUPRESSION APPLIES "EVERYWHERE"



SUPRESSED e_L^+



ALLOWED e_R^+

THERE IS PLENTY OF PHASE SPACE WITH UNSUPRESSED HELICITY STATES.

$$\Gamma(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau) = \frac{G_F^2 m_\tau^5}{192\pi^3}\left[1 - 8\left(\frac{m_\ell}{m_\tau}\right)^2\right]$$

	$\mu \to e$	$\tau \to \mu$	$\tau \to e$
$8\frac{m_\ell^2}{m_L^2}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-2}$	$7 \cdot 10^{-7}$

$\therefore$ EFFECT OF HELICITY SUPRESSION WASHED OUT IN τ AND μ DECAYS.

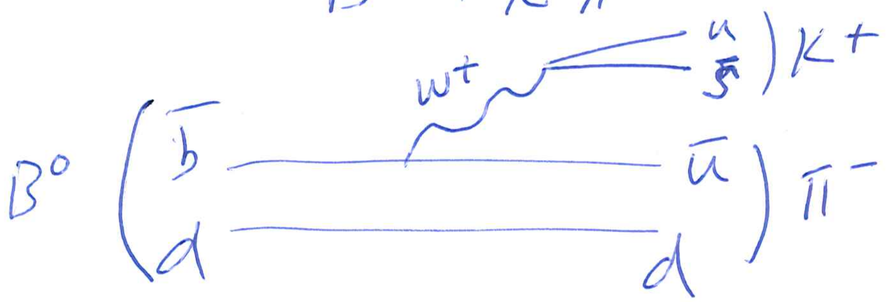
9

DIRECT CP

$$\Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f}), \quad A_{CP} = \frac{\Gamma(A\to f) - \Gamma(\bar{A}\to\bar{f})}{\Gamma(A\to f) + \Gamma(\bar{A}\to\bar{f})}$$

EXAMPLE $B^0 \to K^+\pi^-$

$\bar{B}^0 \to K^-\pi^+$ $\qquad A_{CP} = -0.082 \pm 0.006$



DUE TO A_{CP} WE CAN DEFINE MATTER AND AND ANTIMATTER TO AN ALIEN CIVILIZATION!

BACK TO $K^0 - \bar{K}^0$ SYSTEM

- K_S^0 - REGENERATION
- STRANGENESS OSCILLATIONS

K_S^0 - REGEN

$$|K_L^0\rangle = |K_2^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

AFTER TARGET 2, s REDUCED BY f, $\bar{s}$ BY $\bar{f}$

$$|K'\rangle = \frac{1}{\sqrt{2}}\left(f|K^0\rangle - \bar{f}|\bar{K}^0\rangle\right) = \frac{1}{\sqrt{2}}\left(\frac{f}{\sqrt{2}}(|K_S^0\rangle + |K_L^0\rangle) + \frac{\bar{f}}{\sqrt{2}}(|K_S^0\rangle - |K_L^0\rangle)\right)$$

$$= \frac{1}{2}(f-\bar{f})|K_S^0\rangle + \frac{1}{2}(f+\bar{f})|K_L^0\rangle$$

$f = \bar{f} = 1 \Rightarrow$ NO CHANGE

$f \neq \bar{f} \Rightarrow |K_S^0\rangle$ "RE-GEN"

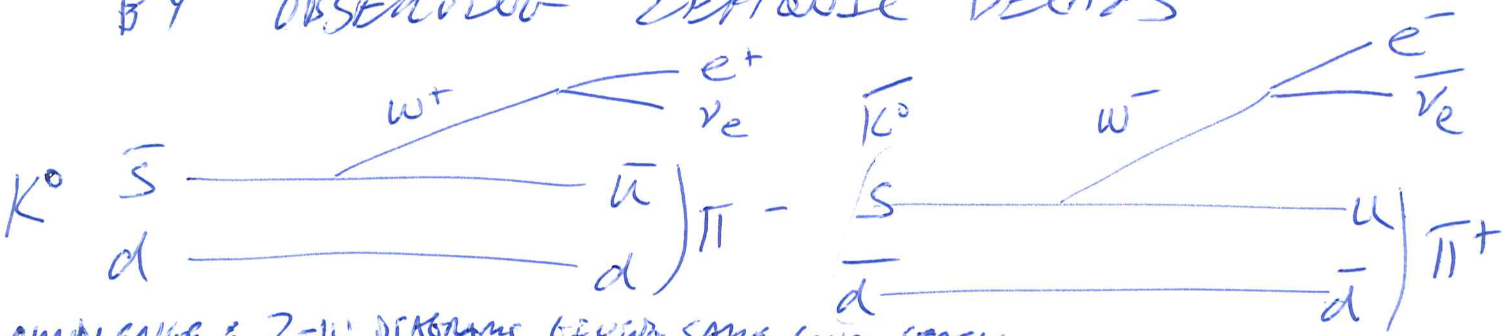
$$\left.\begin{array}{l} K^0 p \to K^+ n \\ \bar{K}^0 n \to K^- p \end{array}\right\} \text{DIFFERENT CROSS-SECTIONS}$$

$\bar{K}^0 p \to \pi^+ \Lambda^0$ — NO COUNTERPART BARYON RESONANCES FOR $K^0 (\bar{s}d)$

IN GENERAL $\bar{F} < F$

- SWITCHING BETWEEN $K^0, \bar{K}^0$ BASIS OF STRONG INTERACTIONS AND $K^0_1, K^0_2 \sim K^0_S, K^0_L$ BASIS OF WEAK INTERACTIONS.

CAN MEASURE $K^0, \bar{K}^0$ CONTENT OF A BEAM BY OBSERVING LEPTONIC DECAYS



CHALLENGE: 2-W DIAGRAMS GIVING SAME FINAL STATE!

STRANGENESS OSCILLATIONS

PRODUCE e.g. K^0 "BEAM" $\pi^- p \to \underset{S=+1}{K^0} \underset{S=-1}{\Lambda^0}$

@ $t=0$ PURE K^0: $|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0_S\rangle + |K^0_L\rangle\right)$

[IGNORE CP HERE FOR SIMPLICITY]

$|K(t)\rangle = \frac{1}{\sqrt{2}}\left(a_S(t)|K^0_S\rangle + a_L(t)|K^0_L\rangle\right)$ Γ_i: DECAY RATE

$a_i(t) = e^{-i m_i t}\, e^{-\Gamma_i t/2}$, $E_i = m_i$ (REST FRAME)

11

WITHOUT OSCILLATIONS

$$I(K_S^0) = a_S^*(t)\,a_S(t)\,\langle K_S^0|K_S^0\rangle$$
$$= I_0 e^{-\Gamma_S t} = I_0 e^{-t/\tau_S}$$

$$|K(t)\rangle = \frac{1}{\sqrt{2}}\left[a_S(t)\frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) + a_L(t)\left(|K^0\rangle - |\bar{K}^0\rangle\right)\right]$$

$$= \frac{1}{2}\left[\left(a_S(t) + a_L(t)\right)|K^0\rangle + \left(a_S(t) - a_L(t)\right)|\bar{K}^0\rangle\right]$$

$$I(K^0(t)) = |\langle K^0|K(t)\rangle|^2 = \frac{I_0}{4}\left[a_S(t) + a_L(t)\right]^2$$

$$= \frac{I_0}{4}\left(a_S^* a_S + a_L^* a_L + a_S^* a_L + a_L^* a_S\right)$$

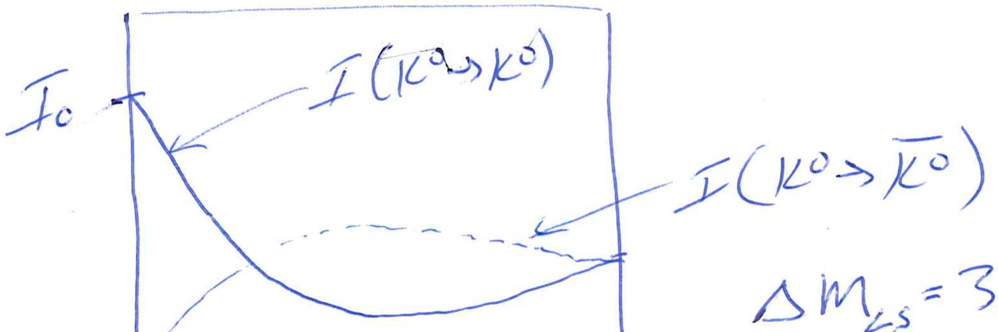
$$= \frac{I_0}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + e^{-(\Gamma_L+\Gamma_S)t/2}\left(e^{i\Delta m t} + e^{-i\Delta m t}\right)\right]$$

$$\Delta m = |m_L - m_S|$$

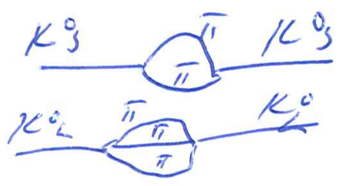
$$I(K^0(t)) = \frac{I_0}{4}\left(e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_L+\Gamma_S)t/2}\cos(\Delta m t)\right)$$

$\vdots$

$$I(\bar{K}^0(t)) = \frac{I_0}{4}\left(e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_L+\Gamma_S)t/2}\cos(\Delta m t)\right)$$



$$\Delta m_{LS} = 3.5 \cdot 10^{-12}\ \text{MeV}$$



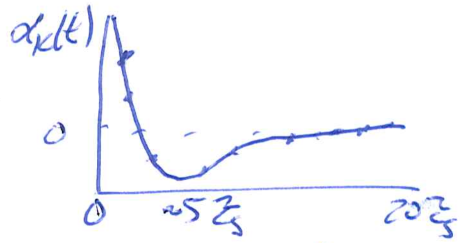
$\to \Delta m$

CAN SHOW THAT $I(K^0 \to K^0) = I(\overline{K^0} \to \overline{K^0})$

$I(K^0 \to \overline{K^0}) = I(\overline{K^0} \to K^0)$

$$\alpha_K(t) = \frac{I(K^0 \to K^0) + I(\overline{K^0} \to \overline{K^0}) - I(K^0 \to \overline{K^0}) - I(\overline{K^0} \to K^0)}{I(K^0 \to K^0) + I(\overline{K^0} \to \overline{K^0}) + I(K^0 \to \overline{K^0}) + I(\overline{K^0} \to K^0)}$$

$$= \frac{2 e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t}{e^{-\Gamma_S t} + e^{-\Gamma_L t}}$$



$\Rightarrow \Delta m = (3.483 \pm 0.006) \cdot 10^{-12}$ MeV WOW!

$p\bar{p} \to K^- \pi^+ \, K^0$

$p\bar{p} \to K^+ \pi^- \, \overline{K^0}$

TAGS THE INITIAL K^0 OR $\overline{K^0}$

MEASURE LEPTONIC DECAYS AND TIME OF DECAY.

CPT: $m_{K^0} = m_{\overline{K^0}}$ $\left| \frac{m_{K^0} - m_{\overline{K^0}}}{m_{K^0}} \right| < 10^{-17}$ (2018)

$\left| \frac{m_{e^+} - m_{e^-}}{m_{e^-}} \right| < 10^{-8}$

IF $\cancel{CP}$ THEN $\cancel{T}$ TO CONSERVE CPT.

11.2.6 FASCINATING BUT BEYOND OVERVIEW.

MUCH SHORTER LIFETIMES THAN KAONS

$B^0 \to f$ BUT $\bar{B}^0 \not\to f$ MANY DECAYS.

B^0_L, B^0_H LIFETIMES $\sim 10^{-12}\,s$

$K^0_{L,S} \cong \frac{1}{\sqrt{2}}\left[|K^0\rangle \pm |\bar{K}^0\rangle\right]$

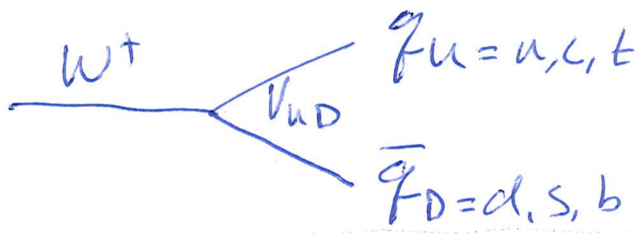
$\cancel{CP}$ BY MIXING SMALL EFFECT — $B^0_{H,L} = \frac{1}{\sqrt{2}}\left[|B^0\rangle \pm \xi|\bar{B}^0\rangle\right]$

$\cancel{CP}$ IN $K^0\bar{K}^0$ IS MOSTLY MIXING

RARE $B^0, \bar{B}^0 \to$ DECAYS EXPENSIVE

<u>INTERFERENCE</u> BETWEEN MIXING AND DIRECT DECAYS

11.3 $\cancel{CP}$ IN STANDARD MODEL



$$V = \text{"}\begin{pmatrix} u \\ c \\ t \end{pmatrix} \times \begin{pmatrix} d & s & b \end{pmatrix}\text{"} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} \cos\theta_c & \sin\theta_c & \sim 0 \\ -\sin\theta_c & \cos\theta_c & \sim 0 \\ \sim 0 & \sim 0 & \sim 1 \end{pmatrix}$$

UNITARITY $V^* V = \mathbb{1}$

$$\begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix}^* \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

9 COMPLEX NUMBERS: 18 PARAMETERS

3 EQN'S THAT GIVE 1

6 EQN'S THAT GIVE 0

5 INDEPENDENT QUARK PHASES

$18 - (3 + 6 + 5) = 3$ ANGLES AND A PHASE $\to \cancel{CP}$

SO FAR THE MATRIX LOOKS UNITARY
AND ALL CP-PHENOMENA CAN BE ACCOUNTED FOR BY COMMON PHASE!

13-b

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$\theta_{12}, \theta_{13}, \theta_{23}$: MIXING BETWEEN PAIRS OF GENERATIONS

δ : CP - PHASE

3 - GENERATION NEUTRINO MIXING

=> COULD ALSO BE A PHASE AND
$\not{CP}$ HERE! TARGET OF LONG-BASELINE
ν - EXPERIMENTS...

BSM — CHAPTER 12

CHALLENGES:
- ARE QUARKS AND LEPTONS 'POINT-PARTICLES'?
- WHY IS GRAVITY SO WEAK?
- WHAT HAPPENS IF YOU GIVE AN ELECTRON THE ENERGY OF A BLACK HOLE?
- CP IN WEAK, WHY NOT IN STRONG-INT.?
- WHAT IS THE NATURE OF DARK MATTER
- WHY ARE NEUTRINOS ALMOST BUT NOT QUITE MASSLESS?
- WHY $q_u = +2/3\,e$, $q_d = -1/3\,e$?
- DOES THE PROTON DECAY?
- WHY IS THE HIGGS MASS $O(M_{W,Z})$?
- IS NATURE SUPERSYMMETRIC?

  FERMIONS $\longleftrightarrow$ BOSONS

  MATTER $\longleftrightarrow$ FORCE
- CAN WE NARROW DOWN THE 10^{500} LOW-ENERGY UNIVERSES FROM STRING-THEORY?
- WHY IS THERE AN EXCESS OF BARYONS?
- MAJORANA NEUTRINOS?
- IS THE SM HIGGS ALONE? IS THE HIGGS SECTOR REALLY SO SIMPLE?
- IS L-R SYMMETRY RESTORED AT HIGHER ENERGY SCALE? ~~W, Z~~ HEAVY W, ν_R
- DO THE 3 FORCES UNIFY AT HIGHER ENERGY SCALE? HOW?

NOT CURRICULUM!