GOLDHABER

CHIRALITY: $\varphi(x) = \underbrace{\tfrac{1}{2}(1+\gamma_5)}_{P_R}\psi + \underbrace{\tfrac{1}{2}(1-\gamma^5)}_{P_L}\psi$

$$= \psi_R + \psi_L$$

only this part of the wavefunction participates to weak int.

FOR NEUTRINOS $(m=0)$ CHIRALITY IS A CONSERVED QUANTITY

$\Rightarrow$ ONLY ν_L AND $\bar{\nu}_R$ EXIST

~~maybe recap on $\bar{\psi}\gamma\psi$?~~

Late 1950s

WU → P violated in weak int

ONLY

θ/τ puzzle → "θ" $\equiv K^+ \to 2\pi \leftarrow P = +1$

"τ" $\equiv K^+ \to 3\pi \leftarrow P = -1$

⇒ $K^\pm$ decay weak

BUT produced STRONG

WHY NOT DECAY STRONG ??

$\tau_{st} \sim 10^{-22}$ s $\qquad \tau_w \sim 10^{-10}$ s

NEW QUANTUM NUMBER : STRANGENESS

conserved by strong int.

violated by weak int.

$K^+ : S = +1 \qquad K^- : S = -1$

$K^+ \overset{\text{str}}{\not\to}$ hadrons

because it's the lightest

particle with $S \neq 0$

eg $\underset{S=1}{K^+} \overset{\text{str}}{\not\to} \underset{S=0}{\pi^+ \pi^+ \pi^-} \qquad \Delta S = 1$

But what about neutral Kaons?

	K^0	$\bar{K}^0$
Q	0	0
B	0	0
S	+1	−1

FIRST NEUTRAL MESON WITH (A) CHARGE

FIRST NEUTRAL BOSON FOR WHICH PARTICLE ≠ ANTIPARTICLE

eg: γ, π^0

What is the nature of $K^0/\bar{K}^0$

they differ only by S, a quantum number not conserved by weak int.

But by now P has fallen but it was thought that CP was a good symmetry of the Universe

real symmetry between matter / antimatter

EG.: $\nu_L + n \rightarrow e^- + p$ ✓ weak

$\xrightarrow{P}$ $\nu_R + n \rightarrow e^- + p$ × ν_R ∄

$\xrightarrow{C}$ $\bar{\nu}_L + \bar{n} \rightarrow e^+ + \bar{p}$ × $\bar{\nu}_L$ ∄

$\xrightarrow{CP}$ $\bar{\nu}_R + \bar{n} \rightarrow e^+ + \bar{p}$ ✓

After fall of P, CP was last bastion standing

So let's look at $K^0 / \bar{K}^0$

Produced strongly $\Rightarrow$ eigenstates of STRONG force

BUT they are <u>NOT</u> eigenstates of CP

$$CP\,|K^0\rangle = |\bar{K}^0\rangle \qquad \left(\begin{array}{l} P\,|K^0\rangle = -1\,|K^0\rangle \\ C\,|K^0\rangle = e^{i\alpha}\,|\bar{K}^0\rangle \end{array} \right)$$

~~e/so~~ and α so that $CP|K^0\rangle = |\bar{K}^0\rangle$

IF CP is conserved

$\Rightarrow$ the physical states are the eigenstates of CP

these are

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle \right) \qquad CP = +1$$

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

We know that both K^0 and $\bar{K}^0$ can decay to 2π 4

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

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

the $(\pi^+\pi^-)$ state has $CP = +1$

In fact both C and P switch the position of the pions $\pi^+ \leftrightarrow \pi^-$

$\Rightarrow$ depends on symmetry of wave function

BUT $L=0$ (because K ~~have~~ have $J=0$)

$$\Rightarrow \quad P = (-1)^{L=0} = +1$$

$$C = (-1)^{L=0} = +1$$

PLUS the intrinsic parity of the pions

$$P(\pi^+) \cdot P(\pi^-) = (-1)(-1) = +1$$

$$\Rightarrow CP = (CP)_{space} \cdot P_{\pi^+} \cdot P_{\pi^-} = +1$$

So if CP is conserved ONLY $|K_1^0\rangle$ can decay to 2π.

$$K_1^0 \rightarrow 2\pi$$
$$K_2^0 \not\rightarrow 2\pi$$

Using similar arguments $CP(3\pi) = -1$

$$\Rightarrow \quad K_1^0 \not\rightarrow 3\pi$$
$$K_2^0 \rightarrow 2\pi$$

$m_\pi \sim 130$ MeV $\quad m_K \sim 500$ MeV

$$\Rightarrow \quad m(3\pi) \lesssim m_K$$

phase space available to 2π decay <u>much</u> LARGER

$$\Rightarrow \text{ expect } \quad \tau(K_1^0) \ll \tau(K_2^0)$$

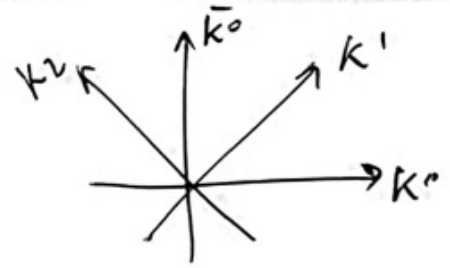
This is why we call them

$K_1^0 = K_S^0$ "short" $\quad \tau_S \sim 0.9 \cdot 10^{-10}$ s

$K_2^0 = K_L^0$ "long" $\quad \tau_L \sim 0.5 \cdot 10^{-7}$ s

$\times 10^3$

RECAP



two representations

STRONG FORCE EIGENSTATES	PRODUCTION	CP EIGENSTATES	TIME EVOLUTION
$\vert K^0\rangle \quad \vert\bar{K}^0\rangle$		$\vert K_1^0\rangle \quad \vert K_2^0\rangle$	

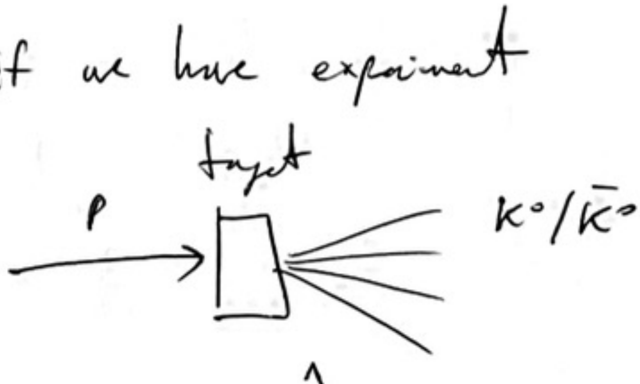
$$|K^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1^0\rangle + |K_2^0\rangle\right)$$

$$|\bar{K}^0\rangle = \frac{1}{\sqrt{2}}\left(|K_1^0\rangle - |K_2^0\rangle\right)$$

$$|K_{1,2}^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle \pm |\bar{K}^0\rangle\right)$$

IF CP CONSERVED these are HAMILTONIAN eigenstates too

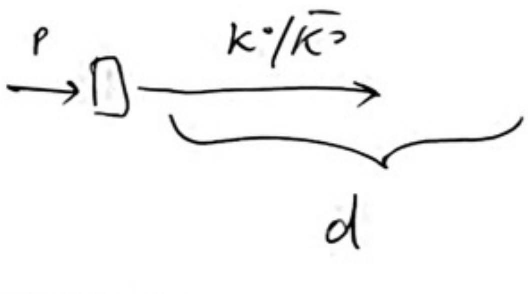
So if we have experiment



KAONS produced in strong interaction

$\Rightarrow$ at $t=0$ $|K^0\rangle$ and $|\bar{K}^0\rangle$

If the $K^0/\bar{K}^0$ travel



time evolution depends on H eigenstates

$$\Rightarrow \quad |K_1^\circ(t)\rangle = e^{-im_1 t - \Gamma_1 t/2} \frac{1}{\sqrt{2}}\left[|K^\circ(0)\rangle + |\bar{K}^\circ(0)\rangle\right]$$

$$|K_2^\circ(t)\rangle = e^{-im_2 t - \Gamma_2 t/2} \frac{1}{\sqrt{2}}\left[|K^\circ(0)\rangle \cancel{+} - |\bar{K}^\circ(0)\rangle\right]$$

FIRST CONSEQUENCE : oscillations

If a state is produced at $t=0$ as purely K° when it propagates it will oscillate

$$K^\circ \to \bar{K}^\circ \to K^\circ$$

with amplitudes

$$\langle K^\circ | \psi(t)\rangle = \frac{1}{2}\left(e^{-im_1 t - \Gamma_1 t/2} + e^{-im_2 t - \Gamma_2 t/2}\right)$$

$$\langle \bar{K}^\circ | \psi(t)\rangle = \frac{1}{2}\left(e^{-im_1 t - \Gamma_1 t/2} - e^{-im_2 t - \Gamma_2 t/2}\right)$$

Second consequence : REGENERATION

Start at $t=0$ with pure K^0 beam in vacuum

50% K_1^0

50% K_2^0

REMEMBER : $\tau(K_1^0) \sim 0.9 \cdot 10^{-10}$ s K_S short

$\tau(K_2^0) \sim 0.5 \cdot 10^{-7}$ s K_L long

$\Rightarrow$ if you wait $10\,\tau_1 \rightarrow$ all K_1^0 decay

$\Rightarrow$ left with only K_2^0

$\Rightarrow$ at $t=0$ 100% $K^0 \Leftrightarrow$ 50% K_1^0 / 50% K_2^0

at $t=10\,\tau_1$ 100% $K_2^0 \Leftrightarrow$ 50% K^0 / 50% $\bar{K}^0$

Now that we have pure K_2^0 beam we make it pass through matter $\Rightarrow$ strong interaction

K^0 and $\bar{K}^0$ are the eigenstates

BUT K^0 and $\bar{K}^0$ have different interaction with matter

$K^0 + p \to K^0 + p$

$K^0 + n \to K^0 + n$

$K^0 + p \to K^+ + n$

$\bar{K}^0 + p \to \bar{K}^0 + p$

$\bar{K}^0 + n \to \bar{K}^0 + n$

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

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

$\bar{K}^0 + n \to \pi^0 + \Lambda^0$

MORE CHANNELS AVAILABLE TO $\bar{K}^0$!

this is because $|\bar{K}^0\rangle = |\bar{d}s\rangle$ ← s quark can swap with one of the quarks in p/n

eg: $|\bar{K}^0\rangle = |\bar{d}s\rangle$

$|p\rangle = |uud\rangle \to |u\bar{d}\rangle = |\pi^+\rangle$

$|uds\rangle = |\Lambda^0\rangle$

$\Rightarrow \bar{K}^0$ interacts more $\Rightarrow |\bar{K}^0\rangle$ component more strongly absorbed

$\Rightarrow$ if you start with 50% K^0 / 50% $\bar{K}^0$

$\rightarrow$ you end up with less $\bar{K}^0$ wrt K^0

BUT so if at $t=0$ $|\psi(t=0)\rangle = 100\% \, |K_2^0\rangle$

50% $\bar{K}^0$ / 50% K^0

then at $t>0$ (in matter) you get different $K^0/\bar{K}^0$ mix

$\Rightarrow$ K_1^0 regeneration

OK BACK TO ORIGINAL QUESTION: if CP conserved

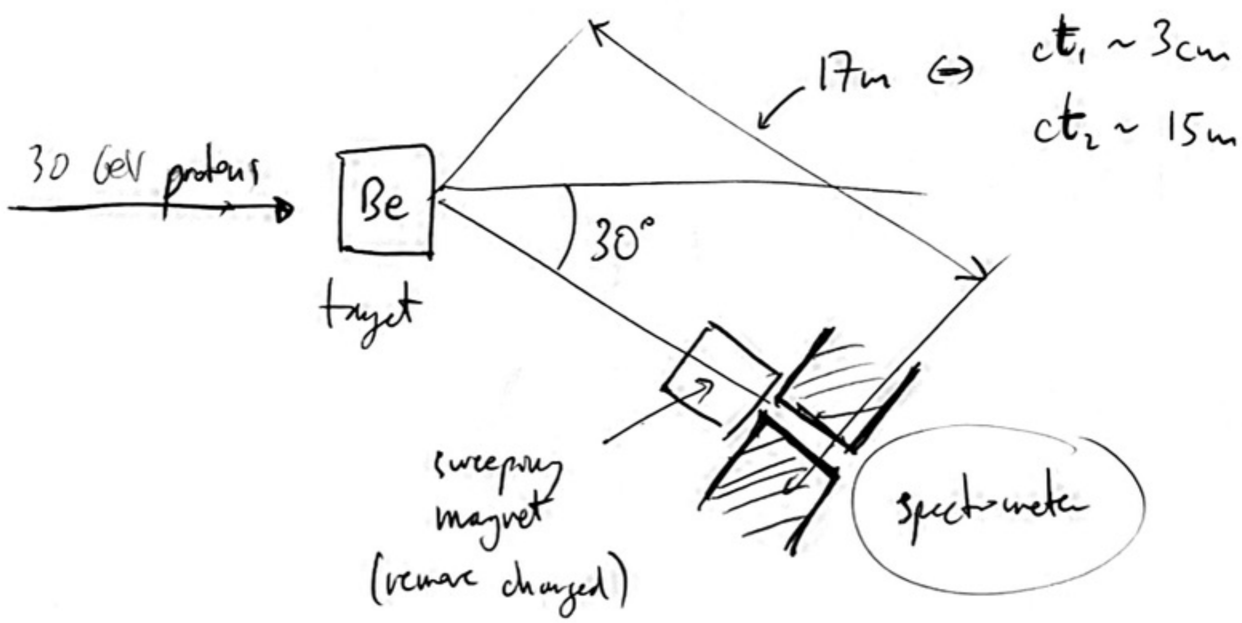
$\Rightarrow$ K_1^0 and K_2^0 are eigenstates of H

$K_1^0 \rightarrow \pi^+\pi^-$ (2π) $\quad CP=+1$

$K_2^0 \rightarrow 3\pi$ $\quad CP=-1$

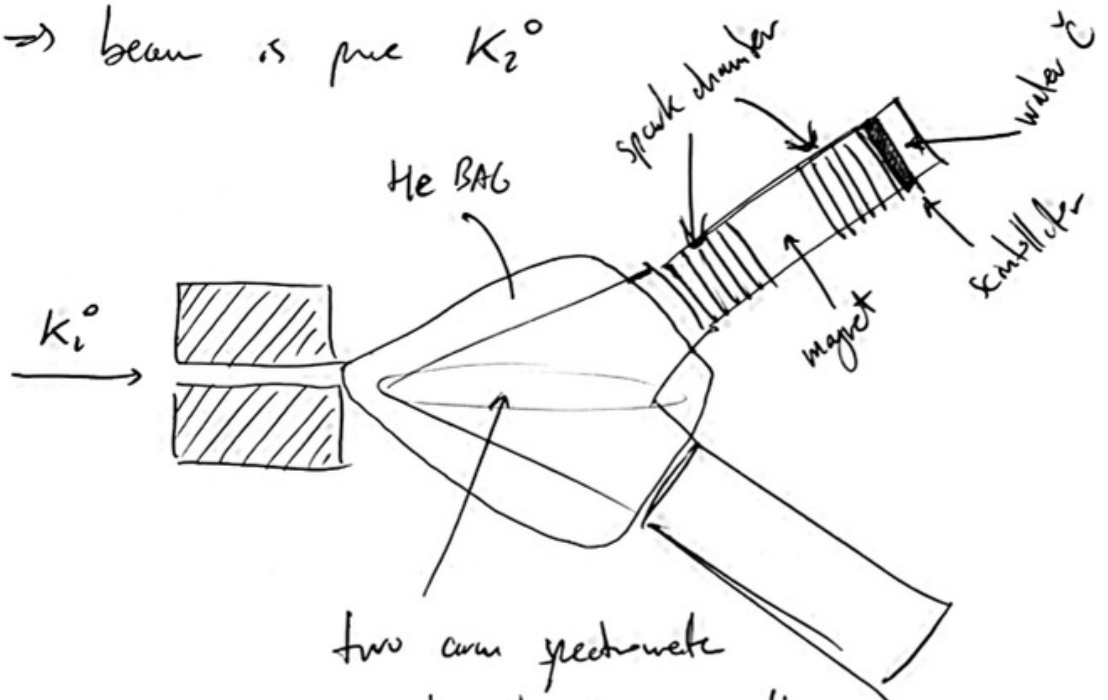
> IF CP GOOD SYMMETRY
> ⚠ $K_2^0 \not\rightarrow 2\pi$

$\boxed{1964}$ CRONIN & FITCH



⇒ at the spectrometer ~~#~~ all K_1^0 have decayed

⇒ beam is pure K_2^0



two arm spectrometer
sensitive to decays in this region

TRIGGER: scintillator + Č
↳ set to $\beta > 0.75$

LOOKING FOR $\underbrace{K_2^0 \to \pi^+ \pi^-}$
CP violating DECAY

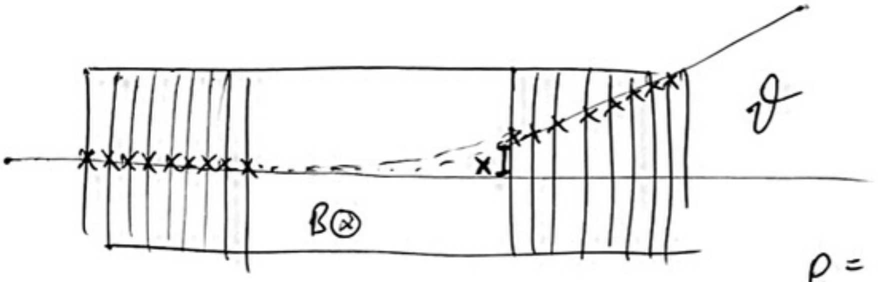
~~BUT FIRST: study K_1^0 regeneration: a piece of tungsten was placed in the decay region~~

~~28 cm steps~~

~~and K_1^0 regeneration was observed in the tungsten block~~

IN ACCORDANCE WITH EXPECTATIONS

spark chambers + magnet ⇒ momentum measurement



$$\rho = \frac{2xB}{\vartheta^2} \quad \left(\begin{matrix}\text{for } q=1 \\ \text{and } \vartheta \ll 1\end{matrix}\right)$$

$$\Rightarrow \vec{p}_1 \text{ and } \vec{p}_2 \xrightarrow{\text{assume } m_\pi} P_1, P_2$$

$$\Rightarrow M(\pi_1, \pi_2) = |P_1 + P_2| \simeq \sqrt{2E_1E_2(1-\cos\alpha)}$$

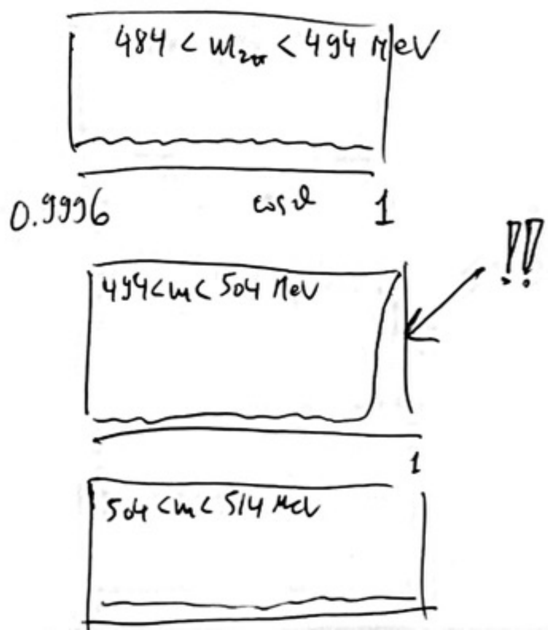
massless approx

(1F) $K_2^\circ \longrightarrow \pi^+\pi^-$

$$\Rightarrow M(\pi^+\pi^-) = M(K_2^\circ) = 498 \text{ MeV}$$

and $\vartheta(\pi^+, \pi^-) = \vartheta(K_2^\circ) = 0$ (initial state)

INSTEAD $K_2^\circ \to (\pi^+\pi^-)\pi^\circ$ does not peak!
(missing a piece)

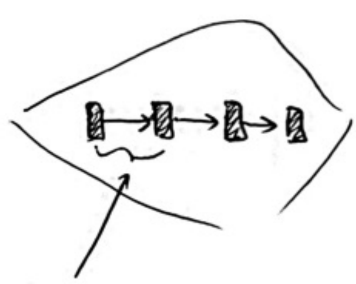


OBSERVATION OF $K_2^\circ \to \pi^+\pi^-$??

Could it be something else?

WHAT ABOUT K_1° REGENERATION IN THE BAG?

to study K_0' regeneration, tungsten target was placed in decay region



and K_0' regeneration observed in the tungsten

in accordance with expectations (calculations)

→ same calculations applied to the gas gave

rate of K_0' regeneration $\sim 10^6$ times LOWER

than observed excess

and

$K_2^0 \to 3\pi$ does not create a peak

ANYTHING ELSE?

$$K_2^0 \to \pi^\pm e^\mp \nu$$
$$K_2^0 \to \pi^\pm \mu^\mp \nu$$

} also misses a part (ν) so no peak

$K_2^0 \to \pi^+\pi^-\gamma$ needs γ with $E_\gamma < 1$ MeV

very rare

$\Rightarrow \quad K_L^0 \to \pi^+\pi^-$!

what does this mean? CP violation

$\Leftrightarrow$ CP eigenstates ~~are~~ not a good set of eigenstates for H

weak/ H eigenstates

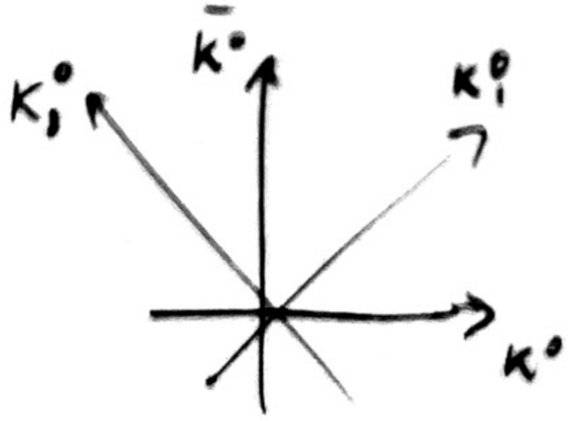
$$K_L^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\left[K_2^0 + \varepsilon K_1^0\right]$$

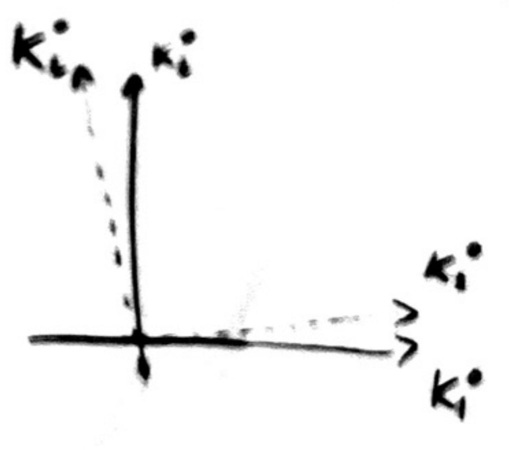
$$K_S^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\left[K_1^0 + \varepsilon K_2^0\right]$$

ε = AMOUNT OF CP VIOLATION IN SM

with $\varepsilon = \dfrac{(K_L^0 \to 2\pi)}{(K_S^0 \to \text{all})} \sim (2.0 \pm 0.4)\, 10^{-3}$

STRONG EIGENSTATES	CP EIGENSTATES	WEAK FORCE EIGENSTATES
$\lvert K^0\rangle \quad \lvert \bar{K}^0\rangle$	$\lvert K_1^0\rangle \quad \lvert K_2^0\rangle$	$\lvert K_L^0\rangle \quad \lvert K_S^0\rangle$





A BRIEF OBITUARY

† 1956 PARITY (WU)

† 1964 CP (CRONIN + FITCH)

BUT CPT holds ← THEOREM

IF CPT falls, whole house comes down

QFT