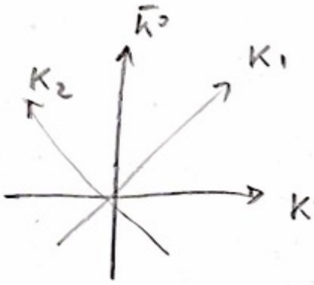
STRONG FORCE EIGENSTATES

$|K^0\rangle \quad |\bar{K}^0\rangle$

CP EIGENSTATES

$|K^0_1\rangle \quad |K^0_2\rangle$

$\tau_1 << \tau_2$



$$|K^0_{1,2}\rangle = \frac{|K^0\rangle \pm |\bar{K}^0\rangle}{\sqrt{2}}$$

IF CP CONSERVED $\Rightarrow$ CP EIGENSTATES = HAMILTONIAN EIGENSTATES

CONSEQUENCES :

1. $K^0/\bar{K}^0$ OSCILLATIONS

IN VACUUM TIME DEVELOPMENT OF K^0_1/K^0_2:

$$|K^0_1(t)\rangle = \frac{e^{-im_1 t - \Gamma_1 t/2}}{\sqrt{2}}\left[|K^0(0)\rangle + |\bar{K}^0(0)\rangle\right]$$

$$|K^0_2(t)\rangle = \frac{e^{-im_2 t - \Gamma_2 t/2}}{\sqrt{2}}\left[|K^0(0)\rangle - |\bar{K}^0(0)\rangle\right]$$

So, if at t=0 you start with a pure K^0 beam

$$|\psi(t=0)\rangle = |K^0\rangle$$

for $t>0$ $|\psi(t)\rangle$ will oscillate between K^0 and $\bar{K}^0$ with amplitudes:

$$\langle K^0|\psi(t)\rangle = \frac{1}{2}\left(e^{-im_1 t - \Gamma_1 t/2} + e^{-im_2 t - \Gamma_2 t/2}\right)$$

$$\langle \bar{K}^0|\psi(t)\rangle = \frac{1}{2}\left(e^{-im_1 t - \Gamma_1 t/2} - e^{-im_2 t - \Gamma_2 t/2}\right)$$

Second consequence ② REGENERATION

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

50% K_1^0
50% K_2^0

Remember: $\tau(K_1^0) \simeq 0.9 \cdot 10^{-10}$ s (K^0 "short")
$\tau(K_2^0) \simeq 0.5 \cdot 10^{-7}$ s (K^0 "long")

$\Rightarrow$ if you ~~wait~~ wait $10\tau_1$ $\rightarrow$ all K_1^0 will have decayed $\Rightarrow$ 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^0_2 we make the beam ~~[illegible]~~ pass through matter 13

$\Rightarrow$ strong interaction

K^0 and K^0 are the eigenstates

K^0 and $\bar{K}^0$ have <u>different</u> interaction with matter

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

$$\bar{K}^0 + p \rightarrow \bar{K}^0 + p$$
$$\bar{K}^0 + n \rightarrow \bar{K}^0 + n$$
$$\bar{K}^0 + p \rightarrow \pi^+ + \Lambda^0$$
$$\bar{K}^0 + p \rightarrow \pi^+ + \Sigma^0$$
$$\bar{K}^0 + p \rightarrow \pi^0 + \Sigma^+$$
$$\bar{K}^0 + n \rightarrow \pi^0 + \Lambda^0$$

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

this because $|\bar{K}^0\rangle = |\bar{d}s\rangle$

s quark can swap with one of the quarks in p/n

e.g. $|\bar{K}^0\rangle = |\bar{d}s\rangle$
$|p\rangle = |uud\rangle$ $\longrightarrow$ $|u\bar{d}\rangle = |\pi^+\rangle$
$|uds\rangle = |\Lambda^0\rangle$

$\Rightarrow$ $\bar{K}^0$ interacts more $\Rightarrow$ $\bar{K}^0$ 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 $t>0$ you get different $K^0/\bar{K}^0$ mix

$\Rightarrow$ K_1^0 REGENERATION

N.B. IN MATTER

OK BACK TO ORIGINAL QUESTION: if CP CONSERVED

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

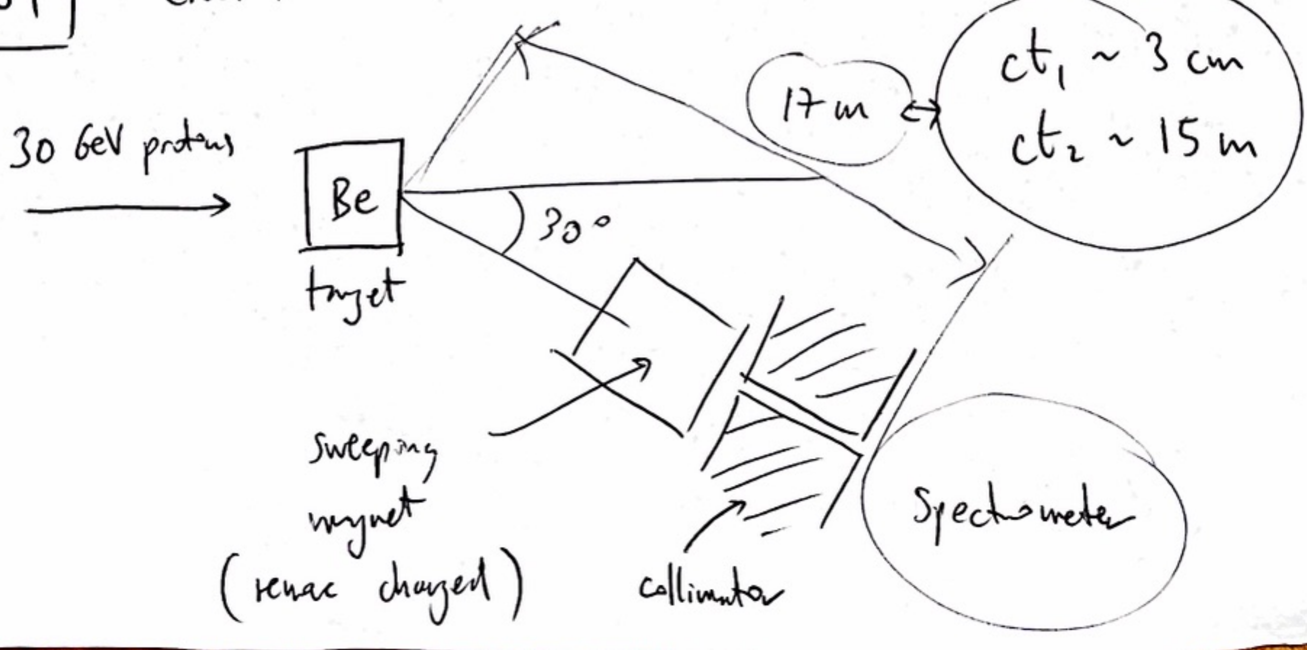
$K_1^0 \rightarrow \pi^+\pi^- (2\pi)$ $\quad CP = +1$

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

⚠ IF CP GOOD SYMMETRY

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

$\boxed{1964}$ CRONIN & FITCH



$d = 17\ m$

$E(p) = 30\ GeV$

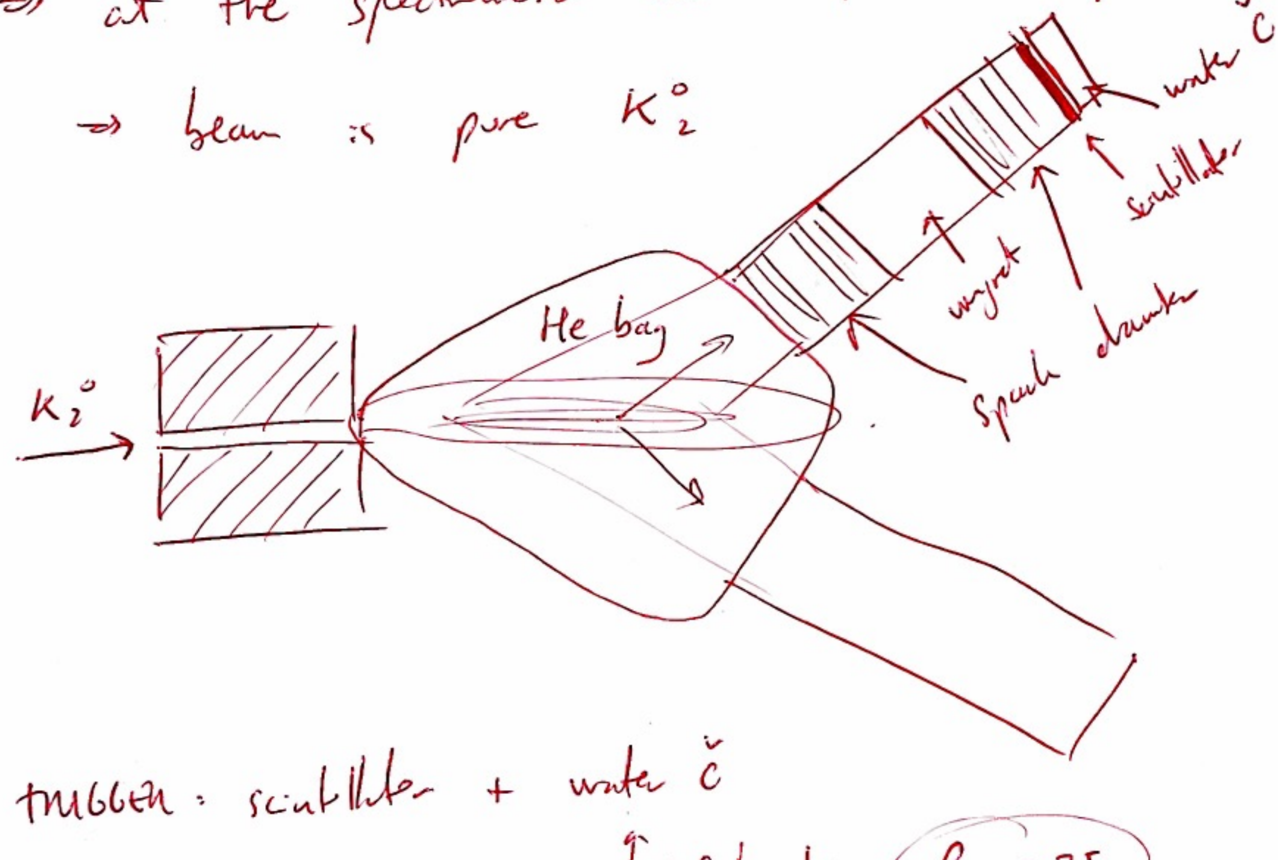
$\Rightarrow$ even if $p(K^0) \sim 30\ GeV$

for $K^0_S \sim 2.3$ cm

$$\Delta x = \beta\gamma c\tau = \frac{p}{m} c\tau = \frac{30 \cdot 10^3}{0.5} = 6 \cdot 10^4 \cdot 2 \cdot 10^{-2} = \simeq 10\ m$$

$\Rightarrow$ at the spectrometer all K^0_1 have decayed

$\Rightarrow$ beam is pure K^0_2



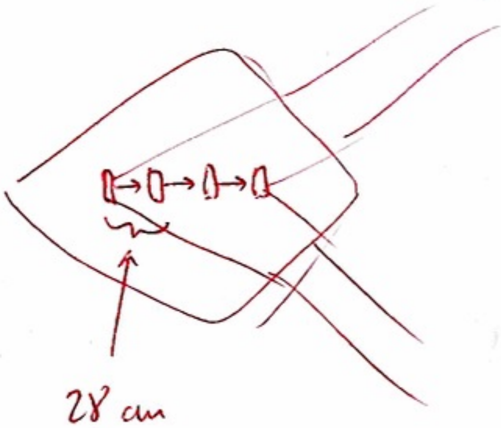
TRIGGER: scintillator + water $\check{C}$

set to $\beta > 0.75$

LOOKING FOR $\underbrace{K^0_2 \to \pi^+\pi^-}$

CP violating decay

(1) To study K^0_1 regeneration a piece of Tungsten was placed in the decay region



and K^0_1 regeneration was observed in the tungsten block, in accordance with expectations

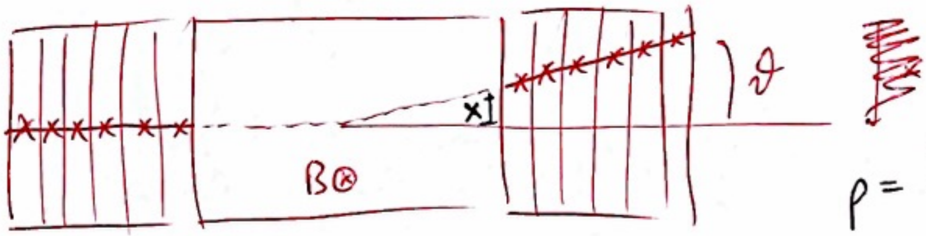
⇒ with the same calculations applied to the gives a rate of K^0_1 regeneration $\sim 10^6$ time lower than observed excess

[$K^0_2 \to 3\pi$ → taking only 2π will not create peak]

(2) $K^0_2 \to \pi^{\pm} e^{\mp} \nu$
$K^0_2 \to \pi^{\pm} \mu^{\mp} \nu$ } works only if neutrino has very specific energy AND very specific angular correlation with π/ℓ to create peak

(3) $K^0_2 \to \pi^+ \pi^- \gamma$ needs $E_\gamma < 1$ MeV

spark chambers + magnet give momentum measurement

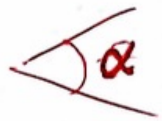


$$p = \frac{2xB}{\vartheta^2} \quad \left(\begin{array}{c}\text{for } q=1 \\ \text{and} \\ \vartheta \ll 1\end{array}\right)$$

$p_1, p_2 \longrightarrow$ assume $m_\pi \longrightarrow P_1, P_2$

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

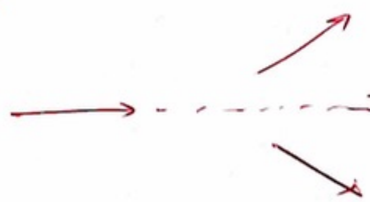
massless approx

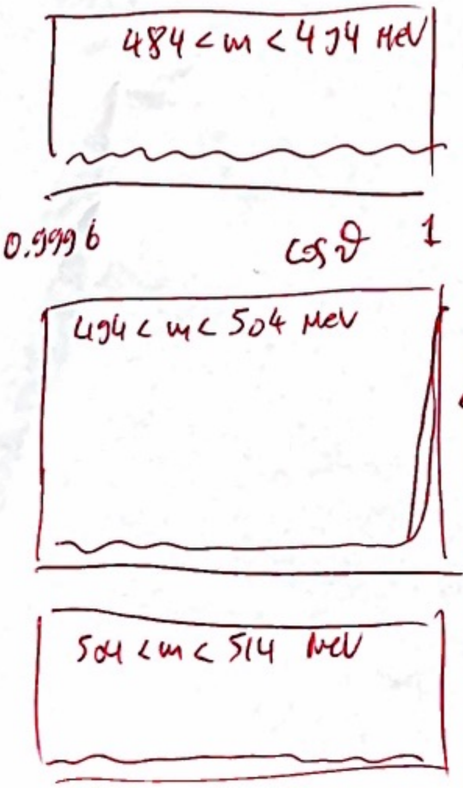


If $K_2^0 \to \pi^+\pi^-$

$$M(\pi^+\pi^-) = M(K_2^0) = 498 \text{ MeV}$$

$$\vartheta(\pi^+,\pi^-) = \vartheta(K_2^0) \sim 0$$





!!

$K_2^0 \to (\pi^+\pi^-)\pi^0$ does not peak!

observation of $K_2^0 \to \pi^+\pi^-$??

Could it be something else?

WHAT ABOUT K_1^0 REGENERATION IN the bag?

$\Rightarrow \quad K_2^0 \to \pi^+\pi^- \quad !$

what does this mean? CP violation

H does not conserve CP

$\Rightarrow$ not a good set of eigenstates

(weak) physical states $\Rightarrow$ H eigenstates

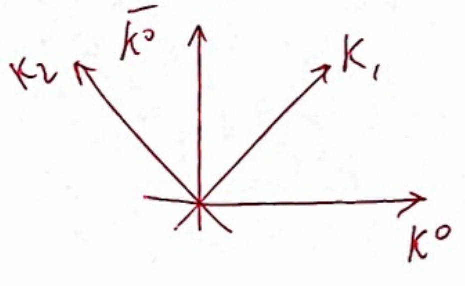
$$K_L^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\left[K_2^0 + \varepsilon K_1^0\right]$$

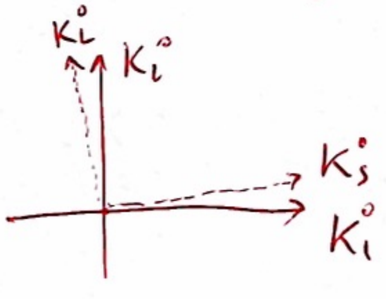
$$K_S^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\left[K_1^0 + \varepsilon K_2^0\right]$$

with $\varepsilon = \frac{(K_2^0 \to \pi^+\pi^-)}{(K_2^0 \to \text{all})} \sim (2.0 \pm 0.4)\cdot 10^{-3}$

parameter of CP violation in SM

STRONG EIGENSTATES	CP EIGENSTATES	WEAK FORCE ~~HAMILTONIAN~~
$\|K^0\rangle$	$\|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(\|K^0\rangle + \|\bar{K}^0\rangle\right)$	$\|K_L^0\rangle = \frac{K_2^0 + \varepsilon K_1^0}{\sqrt{1+\varepsilon^2}}$
$\|\bar{K}^0\rangle$	$\|K_2^0\rangle = \frac{1}{\sqrt{2}}\left(\|K^0\rangle - \|\bar{K}^0\rangle\right)$	$\|K_S^0\rangle = \frac{K_1^0 + \varepsilon K_2^0}{\sqrt{1+\varepsilon^2}}$





A BRIEF OBITUARY

† 1956 PARITY (WU EXPERIMENT)

† 1964 CP (CRONIN FITCH)

CPT holds

THEOREM

if CPT falls the whole system falls

(QFT)