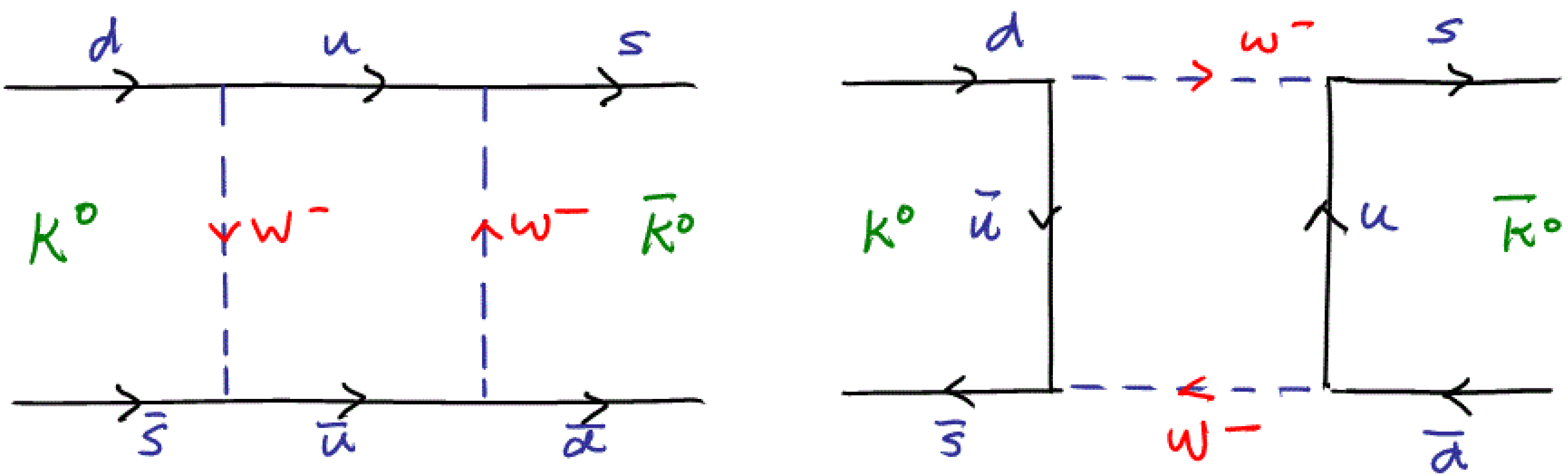
CP CONSERVED IN THE WEAK INTERACTION?

SINCE $|\nu_L\rangle \xrightarrow{CP} |\bar{\nu}_R\rangle$

CP COULD BE A GOOD SYMMETRY OF WEAK FORCE

WEAK FORCE CAN INDUCE

$$|K^0\rangle \xrightarrow{wk} |\bar{K}^0\rangle$$



SECOND ORDER WEAK TRANSITIONS

$|K^0\rangle$ AND $|\bar{K}^0\rangle$ ARE EIGESTATES OF

STRONG INTERACTION

$$\left.\begin{aligned} H_{ST}\,|K^0\rangle &= m_{K^0}\,|K^0\rangle \\ H_{ST}\,|\bar{K}^0\rangle &= m_{\bar{K}^0}\,|\bar{K}^0\rangle \end{aligned}\right\}$$

DEFINITE MASSES

MASSES EQUAL → CPT

$$\left.\begin{aligned} S\,|K^0\rangle &= +1\,|K^0\rangle \\ S\,|\bar{K}^0\rangle &= -1\,|K^0\rangle \end{aligned}\right\}$$

DEFINITE FLAVOUR

⇒ STRANGENESS

STRANGENESS OPERATOR

THEY ARE PRODUCED BY STRONG INTERACTION

→ STRONG EIGENSTATES

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

CAN ONLY DECAY THROUGH WEAK INTERACTION

SINCE

$$|K^0\rangle \xrightarrow{WK} |\bar{K}^0\rangle$$

THESE STRONG EIGENSTATES CANNOT BE EIGENSTATES OF THE WEAK INTERACTION

HYPOTHESIZE THAT WEAK FORCE CONSERVES

CP → T INVARIANCE

$$\left.\begin{aligned} C|K^0\rangle &= |\bar{K}^0\rangle \\ C|\bar{K}^0\rangle &= |K^0\rangle \\ &\text{AND} \\ P|K^0\rangle &= -|K^0\rangle \\ P|\bar{K}^0\rangle &= -|\bar{K}^0\rangle \end{aligned}\right\} \rightarrow \underbrace{\begin{aligned} CP|K^0\rangle &= -|\bar{K}^0\rangle \\ CP|\bar{K}^0\rangle &= -|K^0\rangle \end{aligned}}_{\text{NOT CP EIGENSTATES}}$$

CP CONSERVED IN WEAK INTERACTIONS

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

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

NOT WEAK EIGENSTATES

BUT, THEY ARE A COMPLETE SET OF STRONG EIGENSTATES → CAN CONSTRUCT ANY OTHER STATES OF K^0 $\bar{K}^0$ BY LINEAR SUPERPOSITION OF $|K^0\rangle, |\bar{K}^0\rangle$ INCLUDING WEAK EIGENSTATES

TRY!

$$|K^0_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

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

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

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

$$= +1\ |K_1^0\rangle \rightarrow \text{CP EIGENSTATE}$$

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

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

$$= -1\ |K_2^0\rangle \rightarrow \text{CP EIGENSTATE}$$

$|K_1^0\rangle\ |K_2^0\rangle \rightarrow$ DO NOT HAVE DEFINITE STRANGENESS

↳ OK, NOT CONSERVED BY WEAK

- NOT EIGENSTATES OF S, C, P

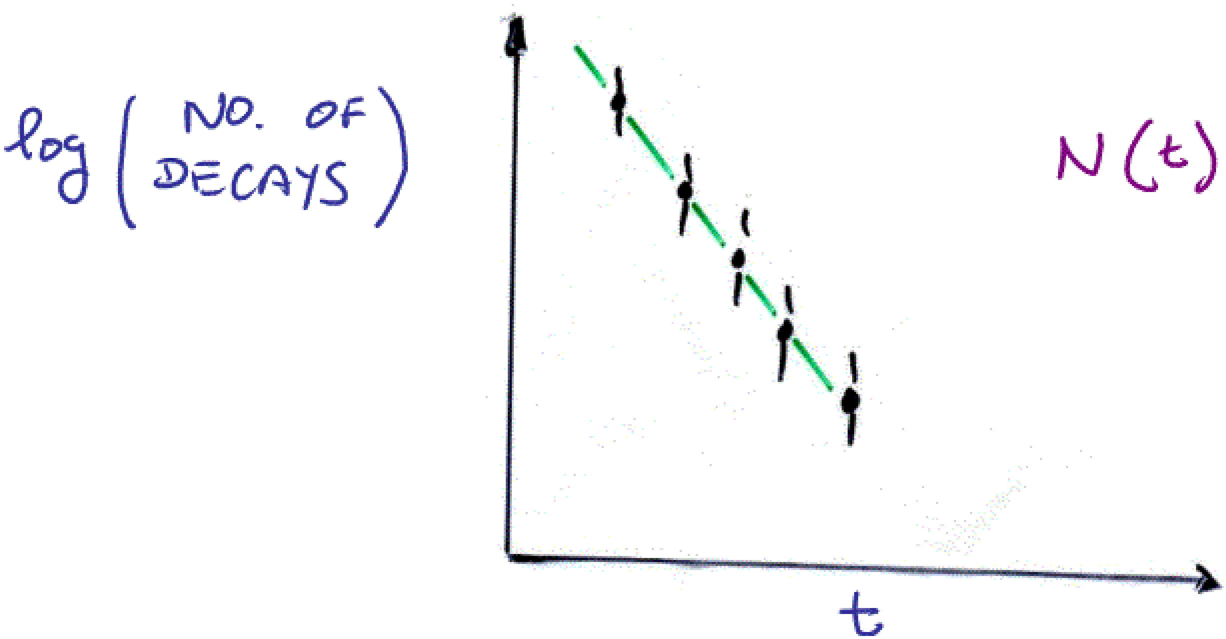
$|K^0\rangle$, $|\bar{K}^0\rangle$ PRODUCED BY STRONG FORCE

$|K_1^0\rangle$, $|K_2^0\rangle$ STATES WE SEE DECAYING BY WEAK FORCE

→ DIFFERENT LIFETIMES & DECAY MODES

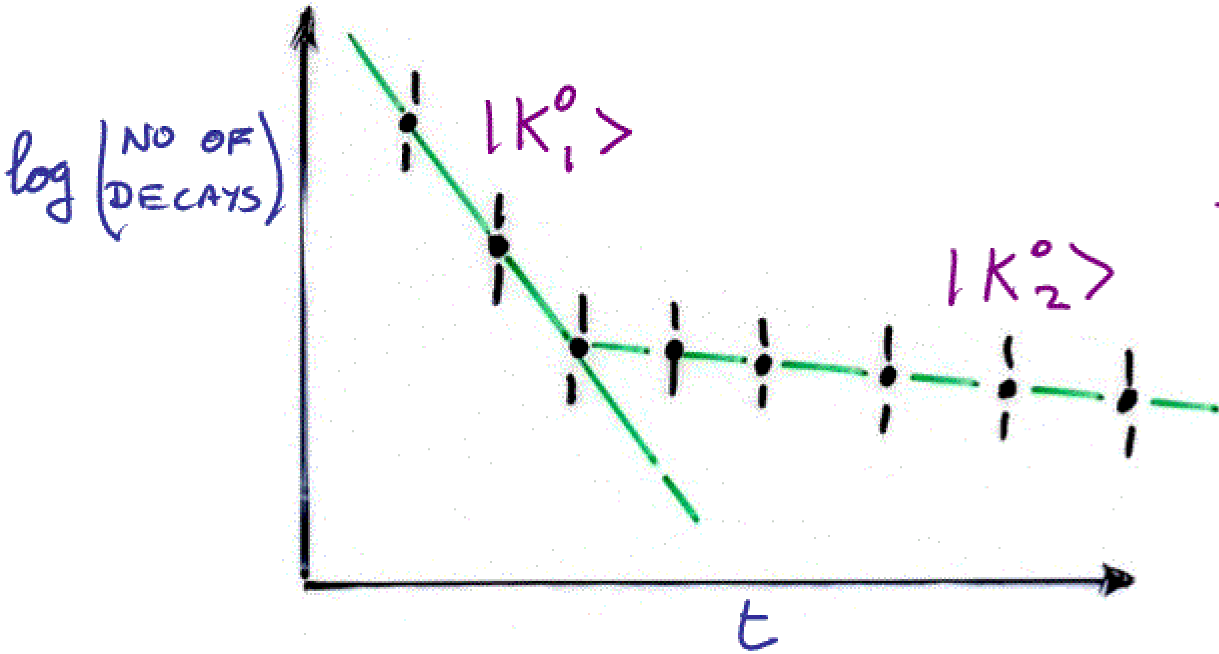
PRODUCE A BEAM OF $|K^0\rangle$ BY STRONG FORCE

IF K^0 DECAYED WITH A SINGLE LIFETIME



$$N(t) = N(0)\, e^{-t/\tau}$$

WHAT ONE SEES EXPERIMENTALLY :



K_1^0 K_2^0 HAVE DIFFERENT LIFETIMES
→ DECAY AT DIFFERENT RATES

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

AFTER SOME TIME $|K_1^0\rangle$ COMPONENT OF BEAM DECAYS → NO LONGER PURE $|K^0\rangle$

→ WEAK INTERACTION SLOWLY CHANGES STRANGESS OF THE BEAM

AT $t=0$

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

CP MIXTURE

$t \gg \tau_{K_1^0}$ $|K_1^0\rangle$ DECAYED

AT $t \gg \tau_{K_1^0}$

$$|\mathrm{BEAM}\rangle = \text{PURE } K_2^0 = |K_2^0\rangle$$

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

WEAK INTERACTION HAS CHANGED

MATTER → MATTER + ANTIMATTER

FAR FROM PRODUCTION OF $|K^0\rangle$ BEAM

HAVE PURE $|K_2^0\rangle \rightarrow CP = -1$ EIGENSTATE

IF CP IS CONSERVED BY WEAK INTERACTION

$$|K_2^0\rangle \rightarrow |CP=-1\rangle \qquad J_\pi^{PC} = 0^{-+}$$

MOSTLY

$$|K_2^0\rangle \rightarrow \pi^+\pi^-\pi^0 \quad CP = -1 \ \checkmark$$

SURPRISE, SURPRISE

$$|K_2^0\rangle \rightarrow \pi^+\pi^- \quad \text{OBSERVED}$$

$$CP = +1$$

$$\frac{\text{No.}(K_2^0 \rightarrow \pi^+\pi^-)}{\text{No.}(K_2^0 \rightarrow \text{ANYTHING})} = 2\times 10^{-3}$$

CP NOT CONSERVED BY WEAK INTERACTION

$CPT \rightarrow$ TIME REVERSAL NON-INVARIANCE

CONSIDER 2π STATE $K_2^0 \to \pi^+\pi^-$

K_2^0, π^+, π^- ALL SPIN $0 \to \ell_{\pi\pi} = 0$ $(-1)^{\ell} = 0$

$$P|\pi^+\pi^-\rangle = + |\pi^+\pi^-\rangle$$

$$C|\pi^+\pi^-\rangle = + |\pi^-\pi^+\rangle$$

$$CP|\pi^+\pi^-\rangle = +1 |\pi^+\pi^-\rangle$$

$$|K_2^0\rangle \to |\pi^+\pi^-\rangle$$

$CP = -1$ $CP = +1$

BOOM !

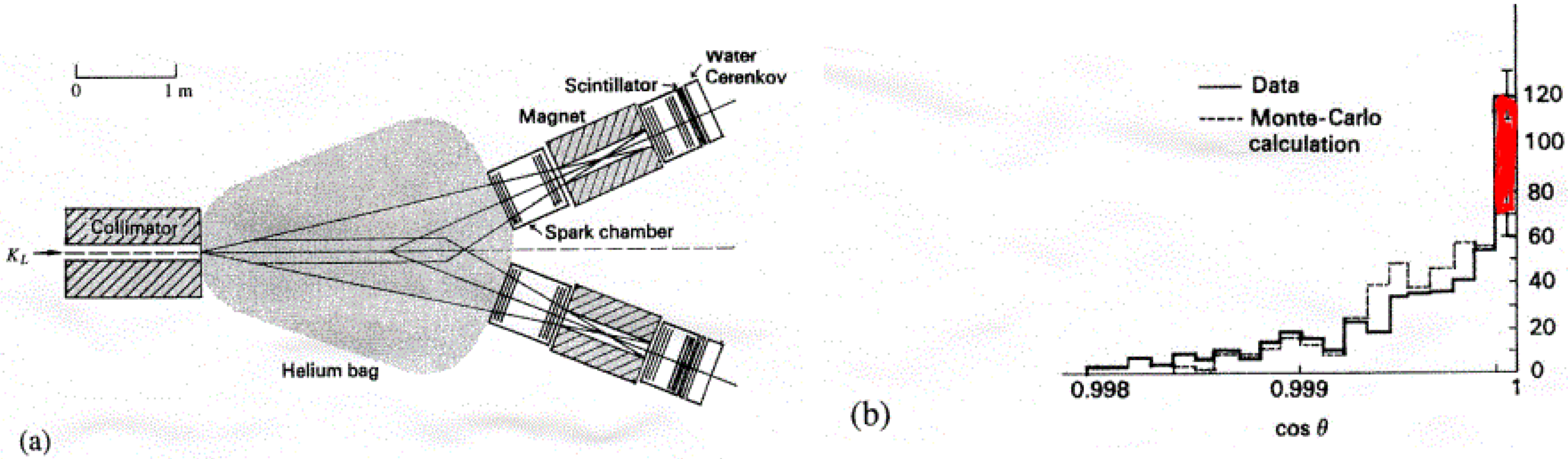


Fig. 7.22. (a) Arrangement of Christenson *et al.* (1964) demonstrating the CP-violating decay $K_L \to \pi^+\pi^-$. K_L decays are observed in a helium bag, the charged products being analysed by two magnet spectrometers instrumented with spark chambers and scintillators. (b) Rare two-pion decays are distinguished from the common three-pion decays by the invariant mass of the pair (490 MeV $< M_{\pi\pi} <$ 510 MeV) and the direction, θ, of the resultant momentum vector. The $\cos\theta$ distribution is that expected from three-body decays, plus 50 events (shaded) collinear with the beam and attributed to the two-pion decay mode.