P and CP violation of the weak decays

The Nobel Prize in Physics 1957
Chen Ning Yang, Tsung-Dao Lee

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Chen Ning Yang

Tsung-Dao Lee

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Tsung-Dao (T.D.) Lee

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

Reminder about parity

The experiment of Wu

$$^{60}\text{Co} \rightarrow {}^{60}\text{Ni}^* + e^- + \bar{\nu}_e. \quad (10.1)$$

So: n → p + e- + $\bar{\nu}$e

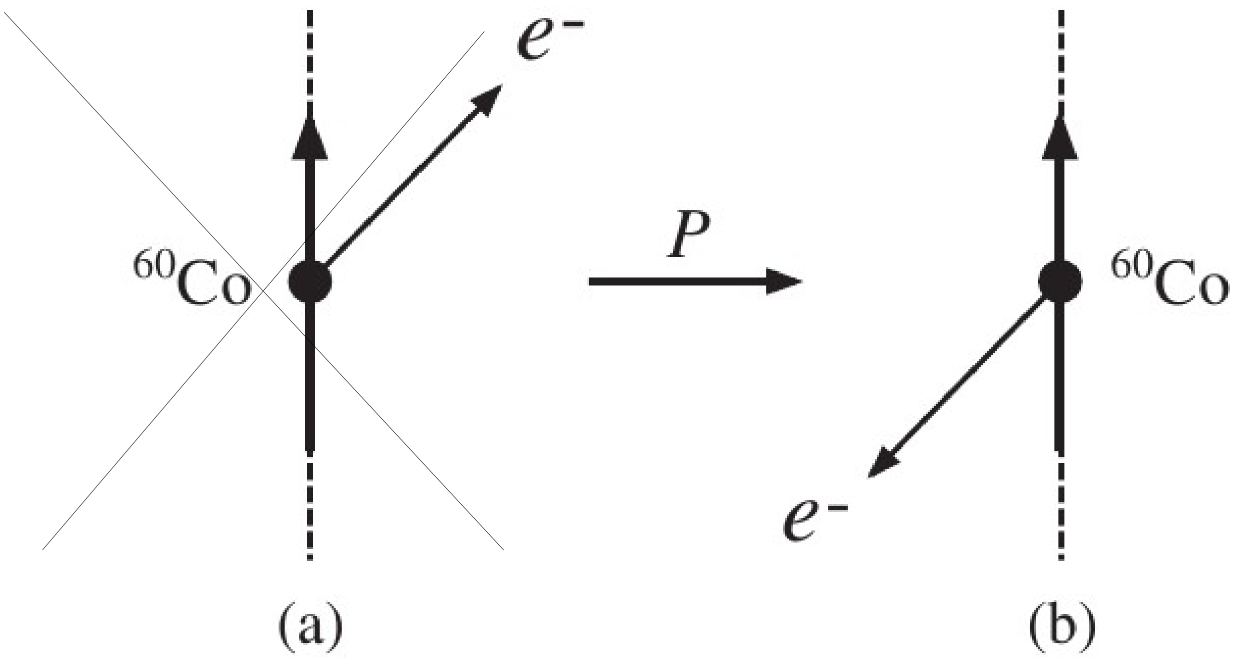


Figure 10.1 Effect of a parity transformation on ^{60}Co decay (10.1). The short thick arrows indicate the direction of the spin of the ^{60}Co nucleus, while the long arrows show the direction of the electron's momentum.

Handedness for massless particles

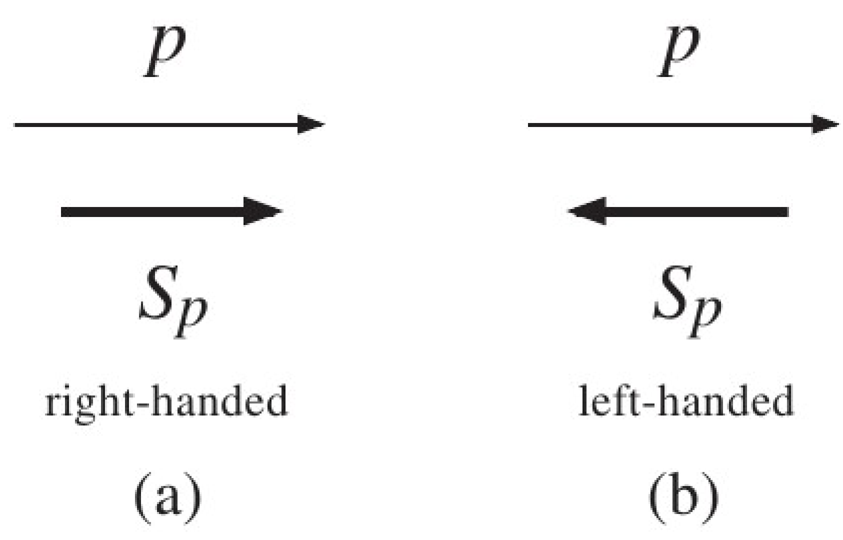
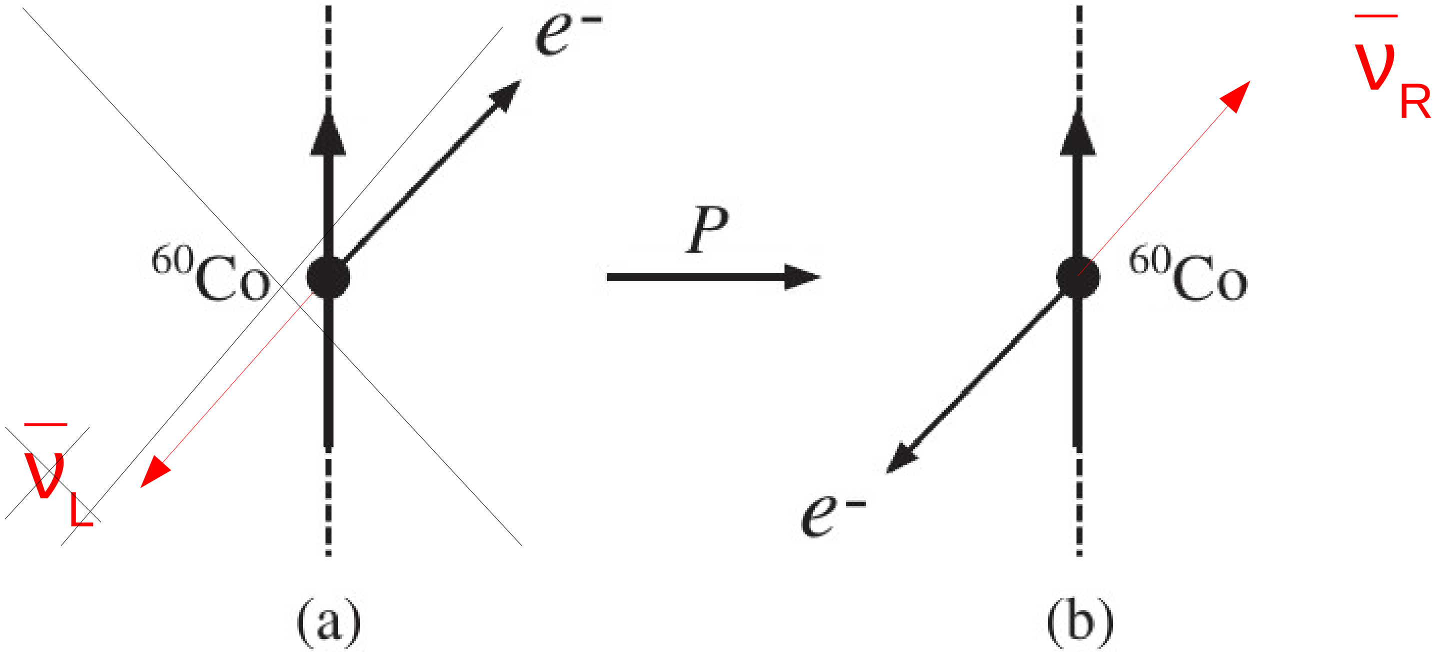


Figure 10.3 Helicity states of a spin-$\frac{1}{2}$ particle. The long thin arrows represent the momenta of the particles and the short thick arrows their spins.

Why only the left is observed

The parent nucleus has the z-component of the spin
Sz = +5, the (excited) daughter nucleus Sz = +4.

So spin of neutrino and electron must point up!



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For neutrinos

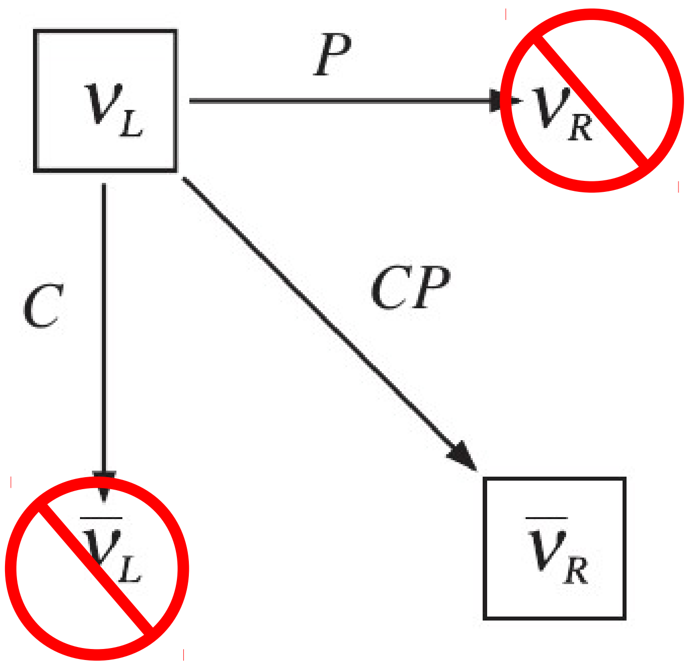
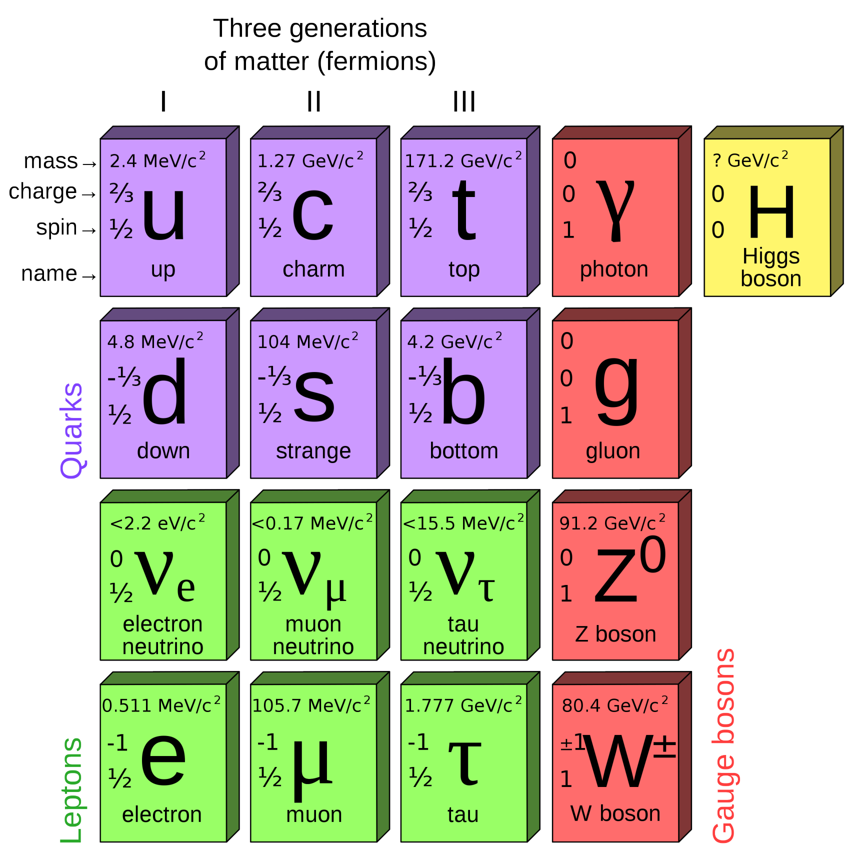
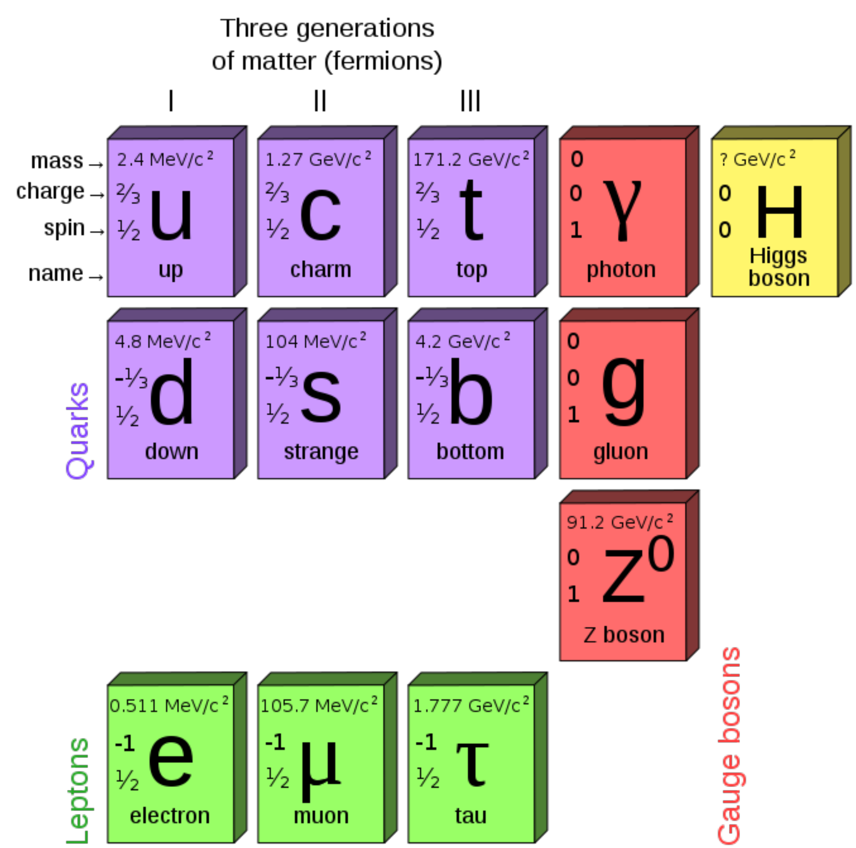


Figure 10.4 Effect of C, P and CP transformations on a left-handed neutrino ν_L. Only the states shown in boxes have been observed in nature.

Left-handed particles & Right-handed anti-particles

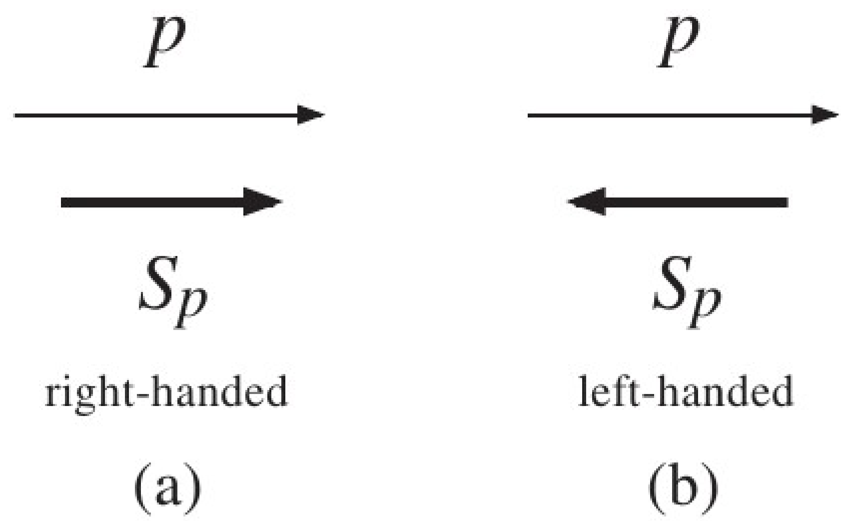


Right-handed particles & Left-handed anti-particles



The Z0 couples different to right handed particles. See e.g. Leif's notes. (This is because the Z0 is a mix beetween B which couples and W0 which does not couple to right handed particles)

Handedness for massive particles



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Handedness is a well defined property for massless particles (coincides with helicity).

For massive particles the handedness can be flipped by a boost!

For a massive particle the forbidden helicity states are only suppressed by:

$$\left(1 - \frac{v}{c}\right) \approx \frac{m^2}{2E^2}, \qquad (10.13)$$

This is also why the pion prefers to decay to a muon!

- Consider:
  - Decay 1: $\pi^- \rightarrow \mu^- + \bar{\nu}\mu$
  - Decay 2: $\pi^- \rightarrow e^- + \bar{\nu}e$
- As pion has spin 0, the e/μ- has to have opposite spin of the anti-neutrino.
- In the CM:

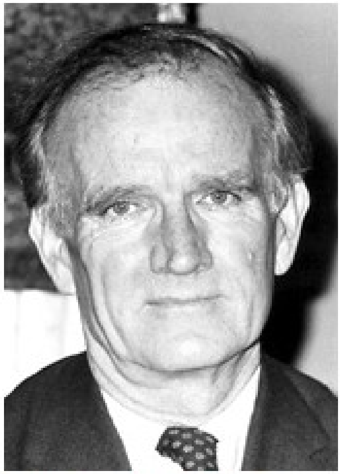
  Momentum: <-------- e-   π- $\bar{\nu}$e -------->

  Spin (only $\bar{\nu}e_R$):   <-------- e-   π- $\bar{\nu}$e -------->
- But the W- coupling to e^-_R is “forbidden”/suppressed!

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = (1.230 \pm 0.004) \times 10^{-4} \qquad (10.15)$$

The Nobel Prize in Physics 1980
James Cronin, Val Fitch

James Watson Cronin

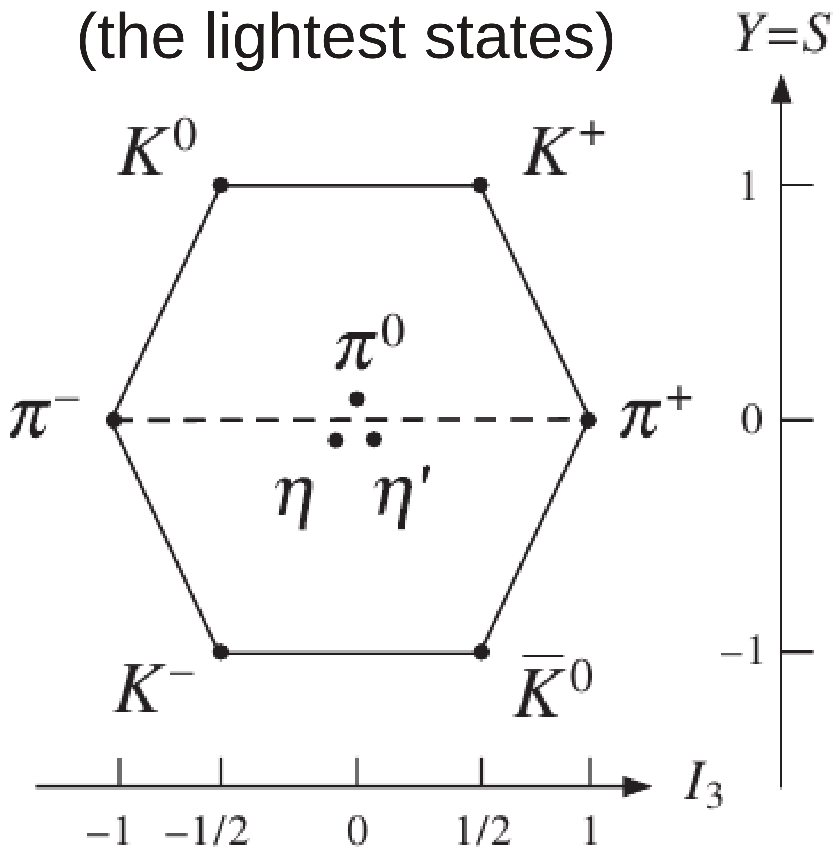


Val Logsdon Fitch

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"*

C and P for the light mesons

The L=0, S=0, J=0 states
(the lightest states)



- Rule for P

$$P_M = P_a P_{\bar{b}} (-1)^L = (-1)^{L+1}.$$

(5.39a)

So these states all have P= -1

- There is no general rule for C
- C=+1 for pions
- C=-1 for K0 and $\overline{\text{K}}$0

K0 $\leftrightarrow$ $\overline{\text{K}}$0 oscillations

$$K^0(498) = d\bar{s} \quad \text{and} \quad \bar{K}^0(498) = s\bar{d}, \tag{10.17}$$

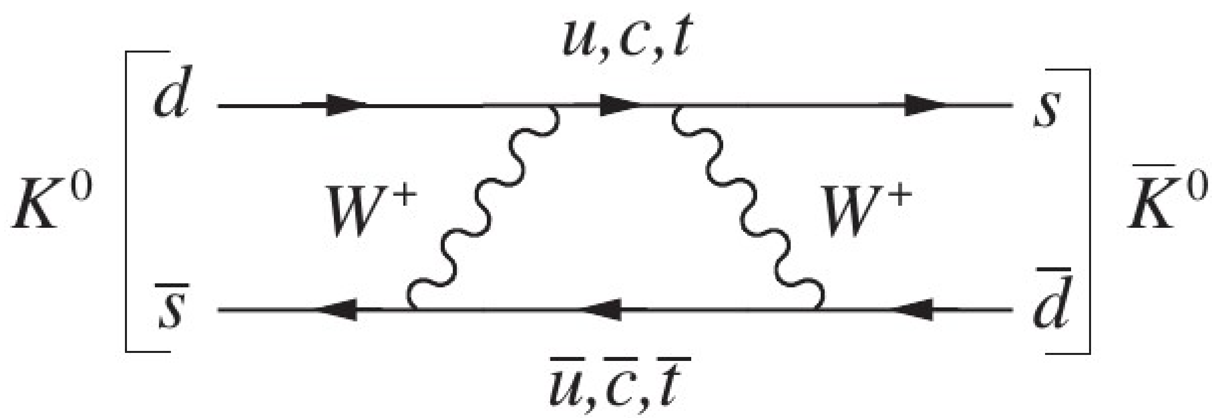


Figure 10.8 Example of a process that can convert a $K^0 \equiv \bar{s}d$ state into a $\bar{K}^0 \equiv s\bar{d}$ state. The labels on the internal lines identify the quark or antiquark going from left to right, i.e. not necessarily in the direction of the arrow.

Question?

$$\left|K_1^0,\ \mathbf{p}=\mathbf{0}\right\rangle \equiv \frac{1}{\sqrt{2}}\left[\left|K^0,\ \mathbf{p}=\mathbf{0}\right\rangle + \left|\bar{K}^0,\ \mathbf{p}=\mathbf{0}\right\rangle\right] \qquad (10.21\text{a})$$

and

$$\left|K_2^0,\ \mathbf{p}=\mathbf{0}\right\rangle \equiv \frac{1}{\sqrt{2}}\left[\left|K^0,\ \mathbf{p}=\mathbf{0}\right\rangle - \left|\bar{K}^0,\ \mathbf{p}=\mathbf{0}\right\rangle\right], \qquad (10.21\text{b})$$

- What is the CP of each state?
- Which state can decay to 2 pions and which to 3 pions?

$$CP\left|K_1^0,\ \mathbf{p}=\mathbf{0}\right\rangle = \left|K_1^0, \mathbf{p}=\mathbf{0}\right\rangle \tag{10.22a}$$

$$CP\left|K_2^0,\ \mathbf{p}=\mathbf{0}\right\rangle = -\left|K_2^0,\ \mathbf{p}=\mathbf{0}\right\rangle, \tag{10.22b}$$

$$K_1^0 \to \pi^+\pi^-,\ \pi^0\pi^0 \tag{10.23a}$$

$$K_2^0 \to \pi^+\pi^-\pi^0,\ \pi^0\pi^0\pi^0 \tag{10.23b}$$

Argument

- Initially J = 0 and as pions have J=0 then L=0
- $P=P_{\pi}^{2} (-1)^{L}$ = 1 (-1 for 3 pions)
- $C=(+1)^{2} (-1)^{L}$ = 1 (also 1 for 3 pions)

The real states

- Experimentally one observes

$$K_S^0 \to \pi^0 + \pi^0, (B = 0.31) \quad \text{and} \quad K_S^0 \to \pi^+ + \pi^-, \ (B = 0.69), \qquad (10.28)$$

with lifetime τ~9x10-11s, and

$$K_L^0 \to \pi^0 + \pi^0 + \pi^0 \ (B = 0.20), \quad K_L^0 \to \pi^+ + \pi^- + \pi^0 \ (B = 0.13) \qquad (10.29)$$

with lifetime τ~5x10-8s, and so we guess

$$K_S^0 = K_1^0 \quad \text{and} \quad K_L^0 = K_2^0. \qquad (10.31)$$

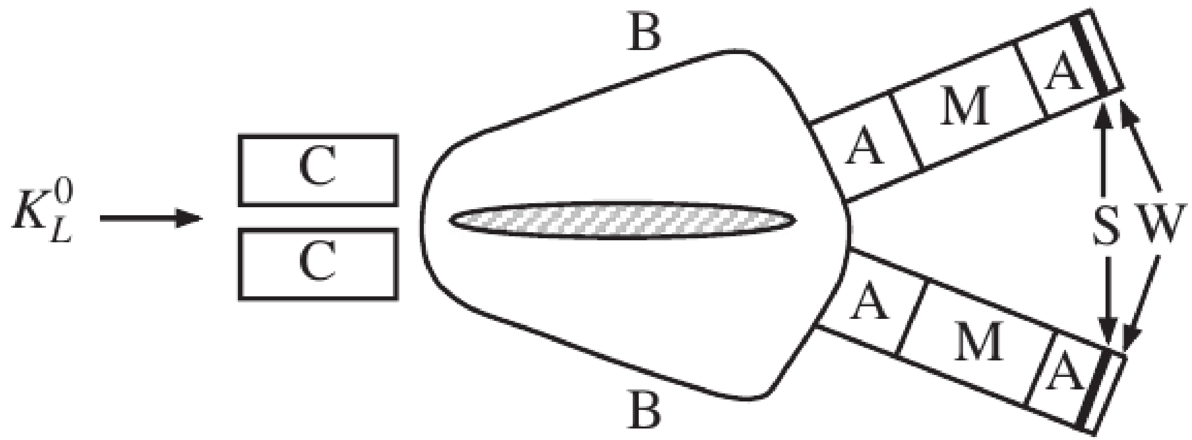
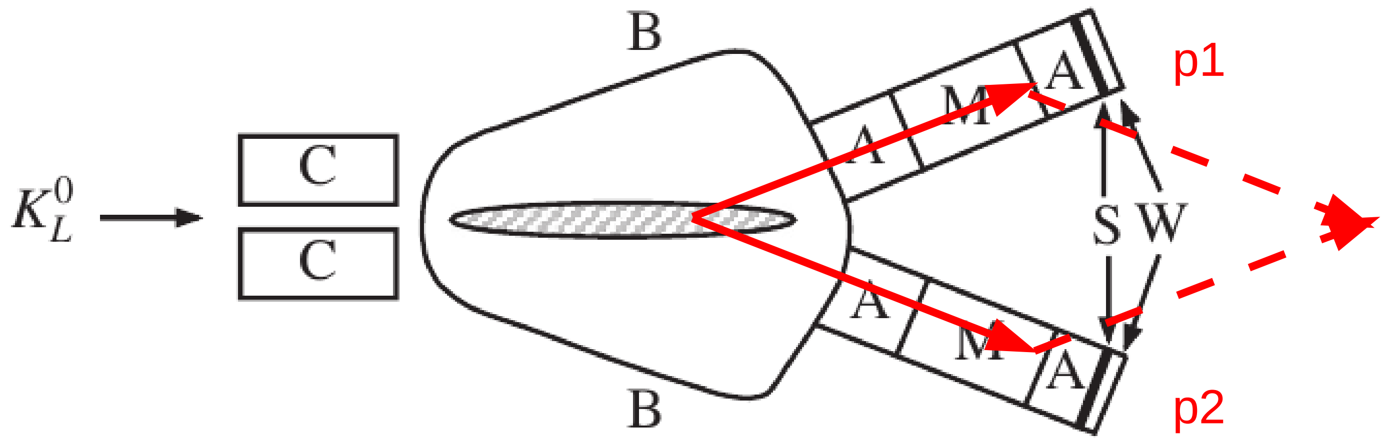


Figure 10.10 Schematic diagram of the apparatus used in the discovery of *CP* violation. The K_L^0 beam entered a helium-filled bag B through a lead collimator C, and those *CP*-violating decays that occurred in the shaded region were detected by the symmetrically spaced spectrometers. These each contained a pair of spark chambers A separated by a magnet M, followed by a scintillation counter S and a water Čerenkov counter W. (Reprinted Figure 1 with permission from J. H. Christenson *et al.*, *Phys. Rev. Lett.*, **13**, 138. Copyright 1964 American Physical Society.)



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Clear signature for CP violating 2 pion decay :
+ and – track, Minv^2 = (p1+p2)^2 ~ MK^2,
sum of 3 momenta parallel to beam

Result

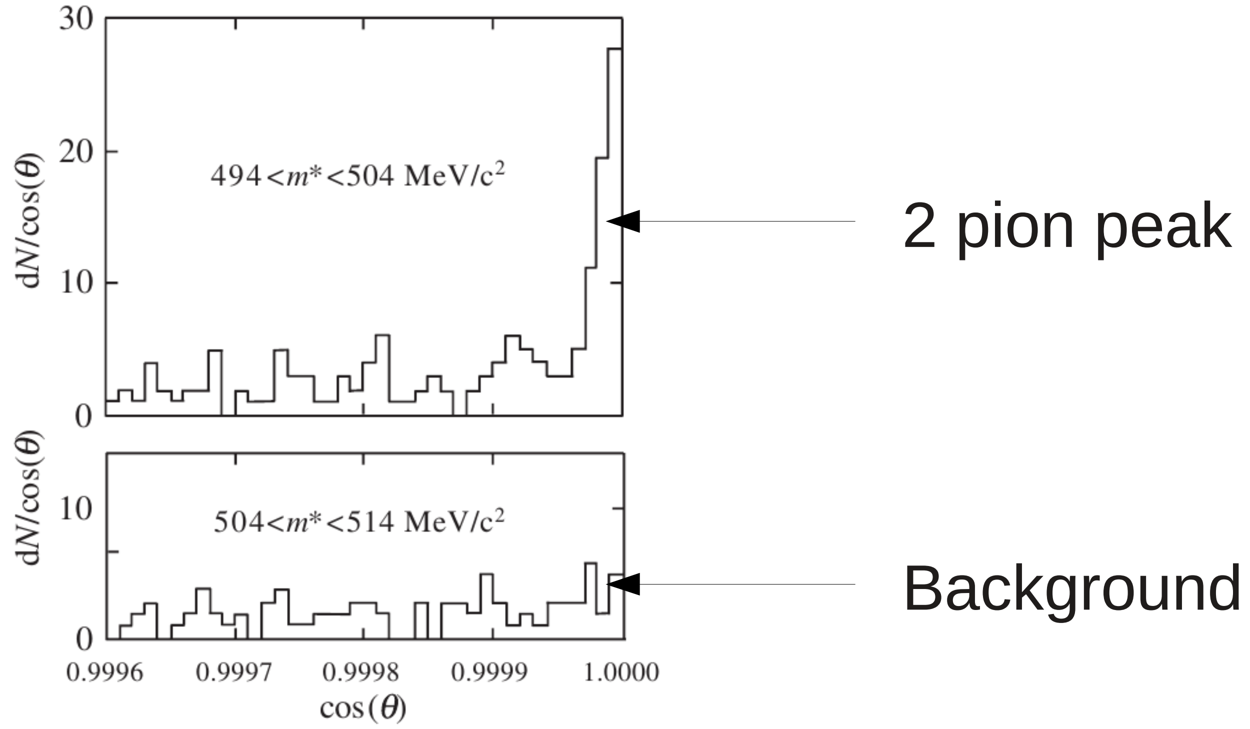

Figure 10.11 Angular distribution of the $\pi^+\pi^-$ pairs detected using the apparatus of Figure 10.10, where θ is the angle between the line-of-flight of the centre-of-mass of the pair and the initial beam direction. Results are shown for an invariant mass range including the K_L^0 mass (498 MeV/c^2) and for a neighbouring mass range. (Reprinted Figure 1 with permission from J. H. Christenson *et al.*, *Phys. Rev. Lett.*, **13**, 138. Copyright 1964 American Physical Society.)

CP is not good symmetry for all weak decays

$$\left| K_S^0, \mathbf{p}=\mathbf{0} \right\rangle = \frac{1}{(1+|\varepsilon|^2)^{1/2}} \left[\left| K_1^0, \mathbf{p}=\mathbf{0} \right\rangle - \varepsilon \left| K_2^0, \mathbf{p}=\mathbf{0} \right\rangle \right] \qquad (10.33a)$$

$$\left| K_L^0, \mathbf{p}=\mathbf{0} \right\rangle = \frac{1}{(1+|\varepsilon|^2)^{1/2}} \left[\varepsilon \left| K_1^0, \mathbf{p}=\mathbf{0} \right\rangle + \left| K_2^0, \mathbf{p}=\mathbf{0} \right\rangle \right], \qquad (10.33b)$$

- So in this case for there is a bit more K0 than $\overline{\text{K}}$0 in K0L

K0L ~ (1+ε)K0 - (1-ε)$\overline{\text{K}}$0

K0S ~ (1-ε)K0 + (1+ε)$\overline{\text{K}}$0

Evidence for mixing

To understand this, we note that the K^0 and $\bar{K}^0$ can decay by the semileptonic reactions

$$K^0 \to \pi^- + e^+ + \nu_e \quad \text{and} \quad \bar{K}^0 \to \pi^+ + e^- + \bar{\nu}_e, \tag{10.35}$$

whereas the corresponding reactions

$$K^0 \to \pi^+ + e^- + \bar{\nu}_e \quad \text{and} \quad \bar{K}^0 \to \pi^- + e^+ + \nu_e \tag{10.36}$$

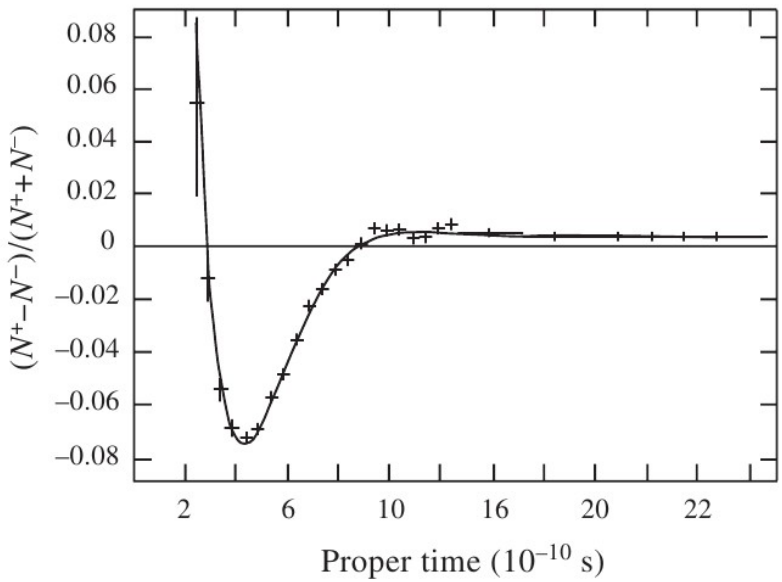

Figure 10.12 The charge asymmetry observed for $K^0 \to \pi^- e^+ \nu_e$ and $\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$ as a function of proper time, for a beam that is initially predominantly K^0. (Reprinted from *Physics Letters B*, **52**, 113 Gjesdal, S., *et al*. Copyright 1974, with permission from Elsevier.)

$$|\varepsilon| = (2.232 \pm 0.007) \times 10^{-3}. \tag{10.41}$$

So nature is not completely symmetric

- We can distinguish between left and right because of the P violation
- We can distinguish between matter and anti-matter because of the CP (C) violation

Also observed in other systems

- **LHCb experiment observes new matter-antimatter difference**
- Geneva, 24 April 2013. The LHCb collaboration at CERN today submitted a paper to Physical Review Letters on the first observation of matter-antimatter asymmetry in the decays of the particle known as the B0s. It is only the fourth sub-atomic particle known to exhibit such behaviour.
- Now the LHCb experiment has observed a preference for matter over antimatter known as CP-violation in the decay of neutral B0s particles......