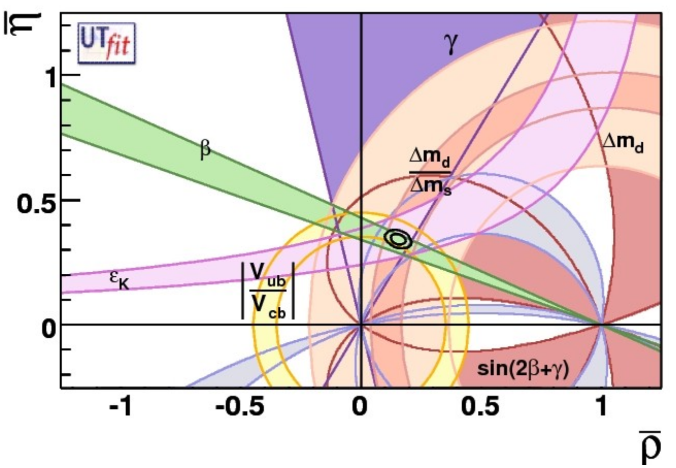
# Flavour Physics and CP Violation





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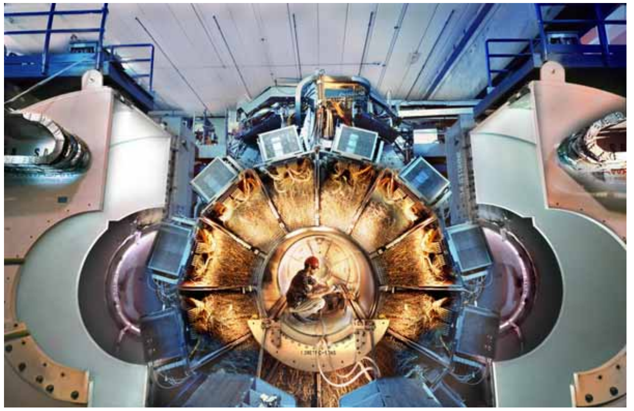


Post-FPCP 2018 Summer School

IIT Hyderabad, India

## Lecture 1

# Outline

- what is flavour physics
- discrete symmetries:
  - P, C, T, CP and CPT
- matter and antimatter
  - Sakarov conditions
  - baryon asymmetry
- CP violation in the Standard Model

# What is flavour physics?

## Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

**Flavour in particle physics**

**Flavour quantum numbers:**

- Baryon number: $B$
- Lepton number: $L$
- Strangeness: $S$
- Charm: $C$
- Bottomness: $B'$
- Topness: $T$
- Isospin: I or $I_3$
- Weak isospin: T or $T_3$
- Electric charge: $Q$
- X-charge: $X$

**Combinations:**

- Hypercharge: $Y$
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: $Y_W$
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

**Flavour mixing**

- CKM matrix
- PMNS matrix
- Flavour complementarity

"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

# Parameters of the Standard Model

- 3 gauge couplinugs + QCD vacuum angle
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

Cabibbo–Kobayashi–Maskawa

CKM matrix

PMNS matrix

Pontecorvo–Maki–Nakagawa–Sakata

flavour parameters

( ) = with Dirac neutrino masses

# What is heavy flavour physics?

$m_u \approx 3$ MeV

$m_d \approx 5$ MeV

$m_s \approx 100$ MeV

$m_c \approx 1300$ MeV

$m_b \approx 4200$ MeV

$m_t \approx 170000$ MeV

$m_{\nu 1} \leq 10^{-6}$ MeV

$m_{\nu 2} \leq 10^{-6}$ MeV

$m_{\nu 3} \leq 10^{-6}$ MeV

$m_e \approx 0.5$ MeV

$m_\mu \approx 100$ MeV

$m_\tau \approx 1800$ MeV

The neutrinos have their own phenomenology

Studies of the u and d quarks are the realm of nuclear physics

Rare decays of kaons provide sensitive tests of the SM

Studies of electric and magnetic dipole moments of the leptons test the Standard Model

Searches for lepton flavour violation are another hot topic

The top quark has its own phenomenology (since it does not hadronise)

# Heavy quark flavour physics

The focus in these lectures will be on:

- CKM matrix as source of CP violation in the Standard Model

Hence specifically

- flavour-changing interactions of beauty quarks
  - charm is also very interesting and I will mention it very briefly

But quarks feel the strong interaction and hence hadronise:

- various different charmed and beauty hadrons
  - many, many possible decays to different final states
  - hadronisation greatly increases the observability of CP violation

# Why is heavy flavour physics interesting?

- ◉ Hope to learn something about the mysteries of the flavour structure of the Standard Model
- ◉ CP violation and its connection to the matter–antimatter asymmetry of the Universe
- ◉ Discovery potential far beyond the energy frontier via searches for rare or SM forbidden processes

# What breaks the flavour symmetries?

◎ In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry

◎ Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_\nu$=0)

◎ The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

◎ Consequently, the only flavour-changing interactions are the charged current weak interactions

- ◉ no flavour-changing neutral currents (GIM mechanism)
- ◉ not generically true in most extensions of the SM
- ◉ flavour-changing processes provide sensitive tests

# What causes the difference between matter and antimatter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks:
  - It is a 3x3 complex unitary matrix described by 4 (real) parameters:
    - 3 can be expressed as (Euler) mixing angles
    - the fourth makes the CKM matrix complex (i.e. gives it a phase)
      - weak interaction couplings differ for quarks and antiquarks
      - CP violation

# Discrete Symmetries

# What do we mean by conservation/violation of a symmetry?

- Define a quantum mechanical operator O.
- If O describes a good symmetry:

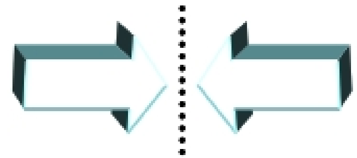
Physics ‘looks the’ same before and after applying the symmetry i.e. the observed quantity associated with O is conserved (same before and after the operator is applied). e.g. conservation of energy-momentum etc.

- If this condition is not met – the symmetry is broken.
  - That is, the symmetry is not respected by nature. So O is (at best) a mathematical tool used to help our understanding of nature.
  - Slightly broken symmetries (like isospin in EW interactions) can be very useful)!

e.g. Isospin symmetry assumes that $m_u=m_d$. In doing so we can estimate branching fractions where the final state differs by a $\pi^0$ vs a $\pi^\pm$ etc. The difference comes from a Clebsch-Gordan coefficient.

# Parity P

- Reflection through a mirror, followed by a rotation of $\pi$ around an axis defined by the mirror plane.
  - Space is isotropic, so we care if physics is invariant under a mirror reflection.



$$\mathbf{r} \to -\mathbf{r}$$
$$\mathbf{p} \to -\mathbf{p}$$
$$\mathbf{L} \to \mathbf{L}$$

- P is maximally violated in weak interactions:

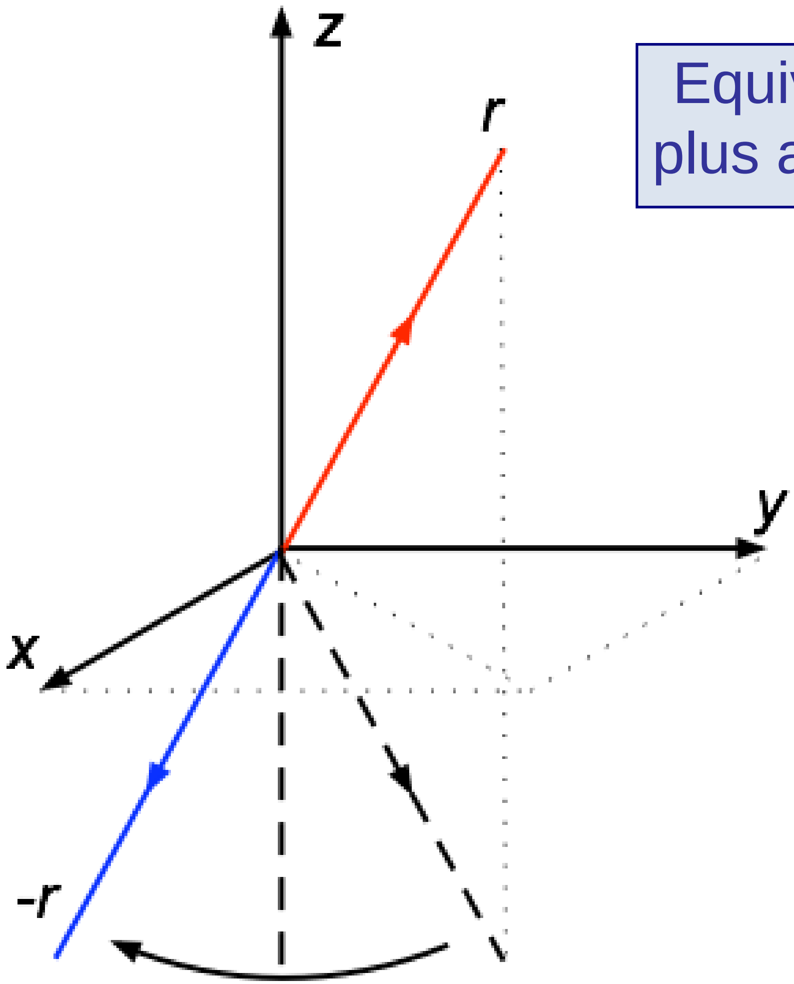
$$[\mathcal{P}, \mathcal{H}_{\mathrm{W}}] \neq 0$$

- Vectors change sign under a P transformation, pseudo-vectors or axial-vectors do not.

- P is a unitary operator: $P^2=1$.

T. D. Lee & G. C. Wick Phys. Rev. **148** p1385 (1966) showed that there is no operator P that adequately represents the parity operator in QM.

# Parity P




Equivalent to a reflection in an x, y mirror plus a rotation through 180° about the z axis

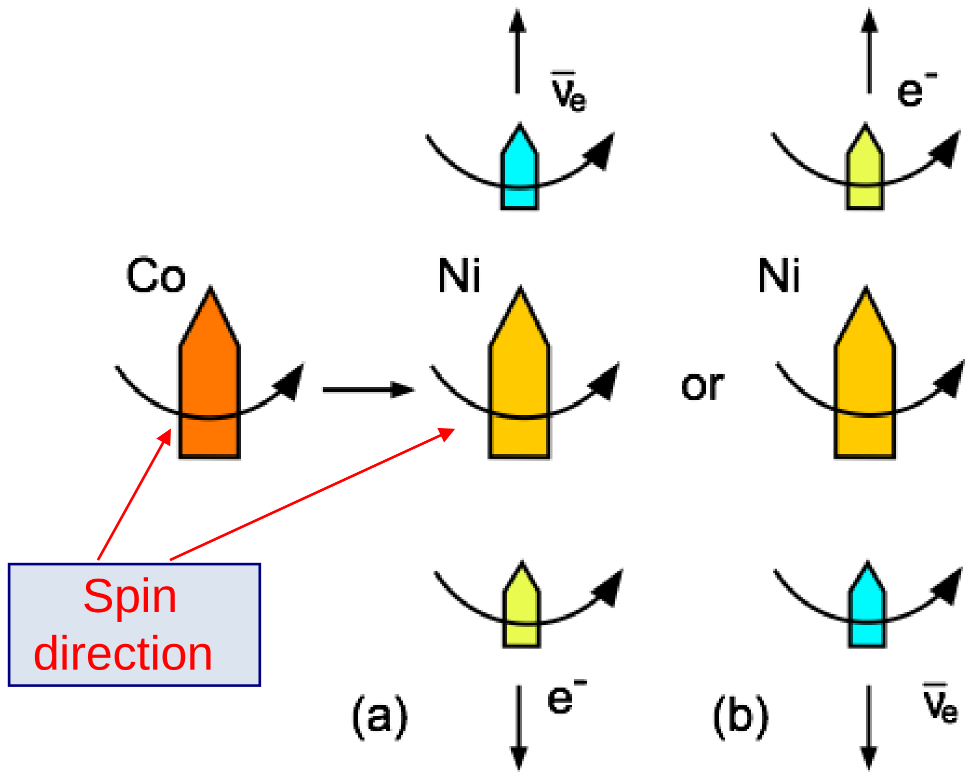
# Parity P

In 1956 if was found that β decay violates parity conservation. It was subsequently found that <u>all</u> weak decays violate parity conservation

In the decay of nuclei with spins aligned in a strong magnetic field and cooled to 0.01° K

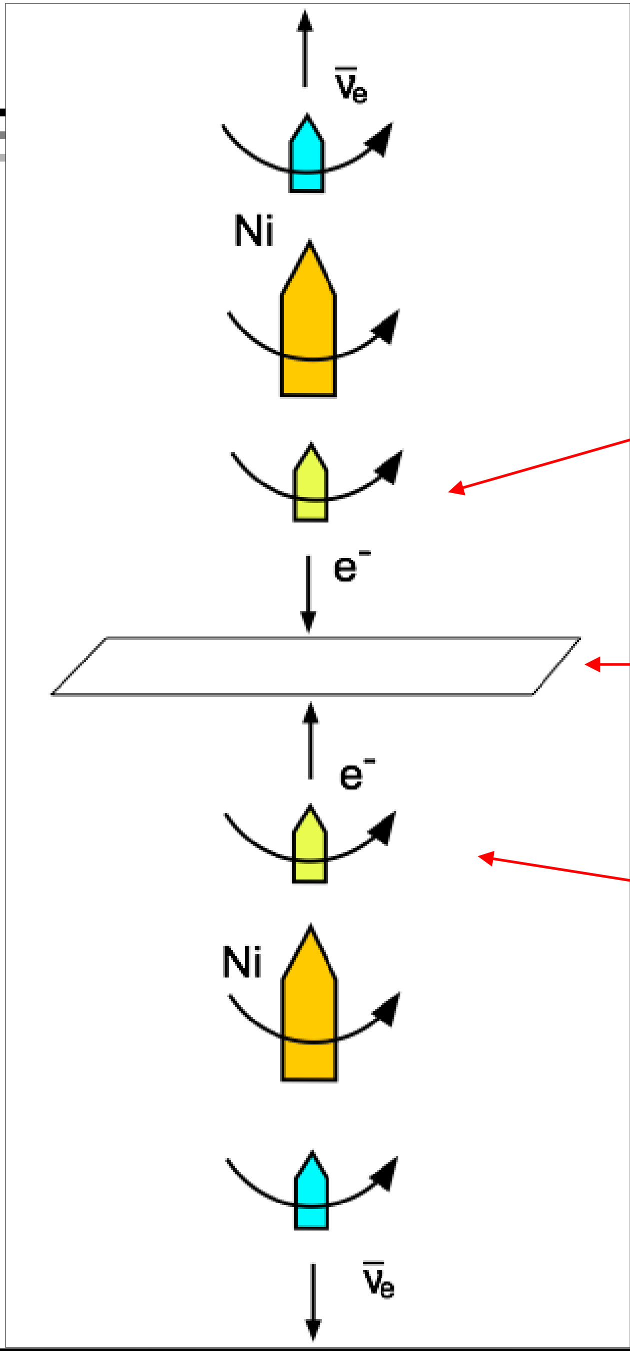
$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

J=5 J=4 J=½ J=½




It was found that electrons were emitted predominantly in configuration (a). If parity were conserved one would expect (a) and (b) equally

# Parity P




Spin and momentum of electron are opposite directions

Mirror

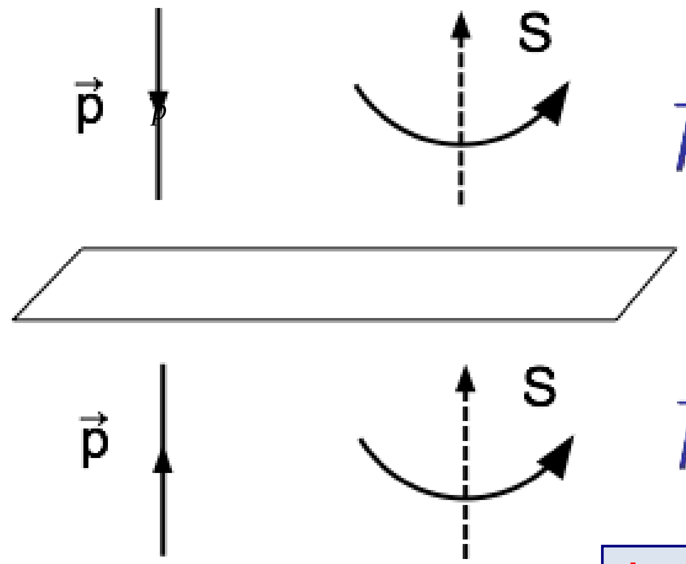
Spin and momentum of electron are the same direction

# Parity P

This is understood as interference between the Vector (V) and Axial Vector (A) parts of the Weak Interaction

$\vec{p}$, $\vec{r}$ etc are Vectors    $\vec{p} \rightarrow -\vec{p}$ under mirror transformations

Spin $\vec{s}$ is an Axial Vector   $\vec{s} \rightarrow \vec{s}$ under mirror transformations




$$\vec{p}\cdot\vec{s} = -|\vec{p}|\,|\vec{s}|$$

$$\vec{p}\cdot\vec{s} = +|\vec{p}|\,|\vec{s}|$$

Any law depending on (Vector) × (Axial Vector) will not conserve parity

The Fermi Matrix Element $M_F \rightarrow M_V - M_A$

$$|M_F|^2 = |M_V|^2 + |M_A|^2 - 2M_V \cdot M_A$$

Interference term gives parity violation

# Aside: helicity

➩ Signed projection of a particle's spin along the direction of its momentum:

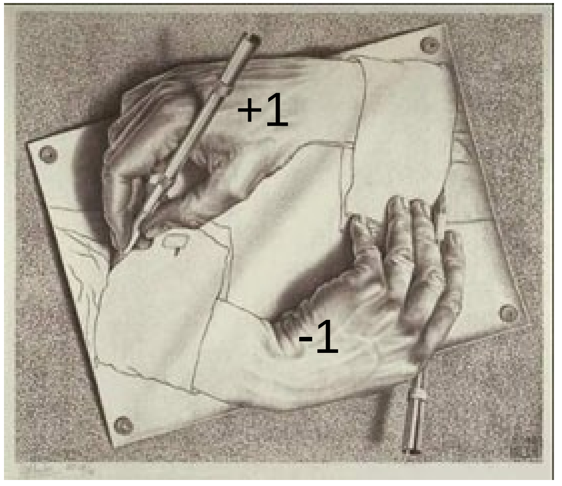
$$h = \frac{\bar{s} \cdot \bar{p}}{|\bar{p}|}$$

$$h \in \{-1, +1\}$$

$$\mathcal{P}(h) = -h$$

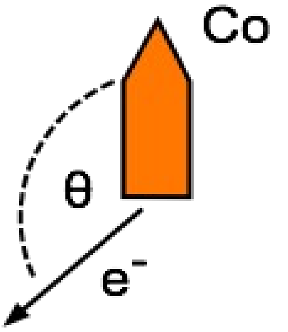
$$\mathcal{C}(h) = h$$

$$\mathcal{T}(h) = h$$



The intensity of emitted electrons from the $^{60}$Co was found to be consistent with a distribution:

$$I(\theta) = 1 + \alpha \frac{(\vec{s} \cdot \vec{p})}{E} = 1 + \alpha \frac{v}{c} \cos\theta$$




The polarisation or Helicity is defined as:

$$H = \frac{I_+ - I_-}{I_+ + I_-} = \alpha \frac{v}{c}$$

Where $I_+$, $I_-$ represent the intensities for $\vec{s}$ and $\vec{p}$ parallel ($\cos\theta = +1$) and for $\vec{s}$ and $\vec{p}$ antiparallel ($\cos\theta = -1$)

# Aside: helicity

Experimentally we find:

$\alpha = +1$ for $e^+$ → $H = +v/c$

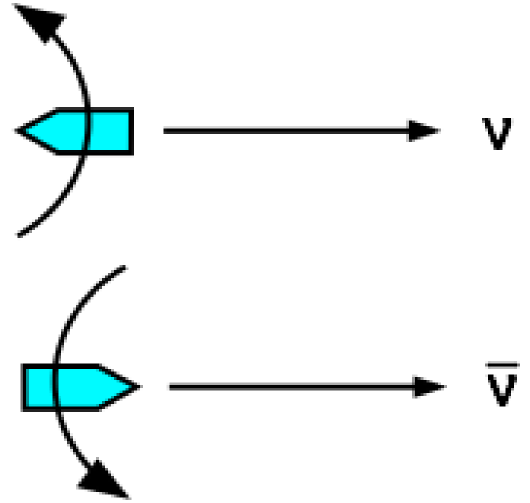
$\alpha = -1$ for $e^-$ → $H = -v/c$

Neutrinos (assuming $m_\nu = 0$ → $v = c$) are fully polarised with $H = +1$ or $-1$

Find neutrinos are always $H = -1$

→ 'Left Handed'

Antineutrinos have $H = +1$



# Aside: helicity and chirality

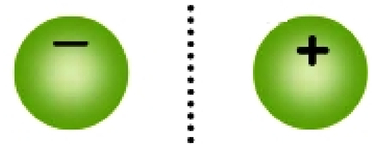
- helicity:
  - projection of the particle spin $\overline{s}$ along the direction of motion $\overline{p}$
    - $\overline{s} \cdot \overline{p} \Rightarrow$ $\overline{s} \uparrow\downarrow \overline{p}$ negative, left helicity

      $\overline{s} \uparrow\uparrow \overline{p}$ positive, right helicity
  - for massive particles (m>0):
    - the sign of the helicity depends on the frame of reference

- chirality or handedness:
  - Lorentz invariant analogue of helicity
    - two states: left-handed (LH) and right-handed (RH)
      - massless particles: either pure RH or LH
      - massive particles: both LH+RH components
    - helicity eigenstate is a combination of handedness states

# Charge Conjugation: C

- Change a quantum field $\phi$ into $\phi^\dagger$, where $\phi^\dagger$ has opposite U(1) charges:
  - *baryon number, electric charge, lepton number, flavour quantum numbers like strangeness & beauty etc.*




$$e^- \rightarrow e^+$$

$$\gamma \rightarrow \gamma$$

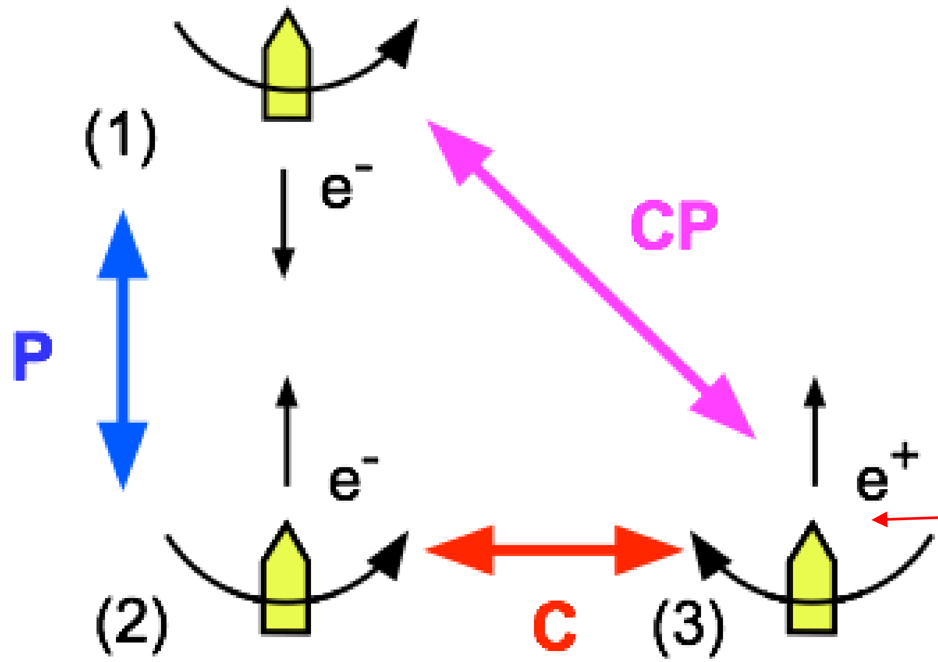
- Change particle into antiparticle.
  - *the choice of particle and antiparticle is just a convention.*
- C is violated in weak interactions, so matter and antimatter behave differently, and:

$$[\mathcal{C}, \mathcal{H}_W] \neq 0$$

- C is a unitary operator: $C^2=1$.

# Parity and Charge Conjugation: CP

Note that Charge Conjugation C is also violated but CP is (usually) conserved




Charge Conjugation C changes particle into antiparticle

(3) is again a favourite configuration from the point of view of weak interaction, just like (1) was.

# Parity and Charge Conjugation: CP

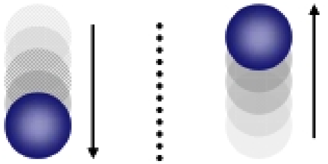
The fundamental point is that CP symmetry is broken in any theory that has complex coupling constants in the Lagrangian which cannot be removed by any choice of phase redefinition of the fields in the theory.

- Weak interactions are left-right asymmetric.
  - *It is not sufficient to consider C and P violation separately in order to distinguish between matter and antimatter.*
  - *i.e. if helicity is negative (left) or positive (right).*
- CPs a unitary operator: $CP^2=1$

# Time reversal: T

Not to be confused with the classical consideration of the entropy of a macroscopic system.

- ‘Flips the arrow of time’
  - *Reverse all time dependent quantities of a particle (momentum/spin).*
  - *Complex scalars (couplings) transform to their complex conjugate.*
  - *It is believed that weak decays violate T, but EM interactions do not.*




- T is an anti-unitary operator: $T^2$=-1.

# Summary on discrete symmetries

Three discrete operations are potential symmetries of a field theory Lagrangian.

*Two of them, parity and time reversal are space-time symmetries.*

- Parity sends $(t; x) \to (t; -x)$, reversing the handedness of space.
- Time reversal sends $(t; x) \to (-t; x)$, interchanging the forward and backward light-cones.

*A third (non-space-time) discrete operation is:*

- Charge conjugation: it interchanges particles and anti-particles.

The operators associated to these symmetries have different properties:

- *P and C operators are:*
  - → unitary and thus they satisfy the relation $U^T = U^{-1}$
  - → linear and thus $U(\alpha|a\rangle + \beta|b\rangle) = \alpha\, U|a\rangle + \beta\, U|b\rangle$.
- *T operator is anti-unitary, that means that is satisfies*
  - → the unitary relation: $A^T = A^{-1}$
  - → but it is anti-linear: $A(\alpha|a\rangle + \beta|b\rangle) = \alpha^*\, A|a\rangle + \beta^*\, A|b\rangle$.

# CPT

- all locally invariant Quantum Field Theories conserve CPT[1].
- CPT is anti-unitary: $CPT^2=-1$.
- CPT can be violated by non-local theories like quantum gravity. These are hard to construct.
  - *see work by Mavromatos, Ellis, Kostelecky etc. for more detail.*
- If CPT is conserved, a particle and its antiparticle will have
  - *The same mass and lifetime .*
  - *Symmetric electric charges.*
  - *Opposite magnetic dipole moments (or gyromagnetic ratio for point-like leptons).*

[1]See Weinberg volume I and references therein (Lueders 1954) for a proof of this.

# Broken symmetries

- The symmetry CPT is conserved in the Standard Model.
- The other symmetries introduced here are broken by some amount.
- CP violation has been seen in kaon and B meson decays.
- These symmetries are broken for weak interactions only!
  - *They are conserved (as far as we know) in strong and electromagnetic interactions.*

# Summary on CP and CPT

The combination CPT is an exact symmetry in any local Lagrangian field theory:

- The CPT theorem is based on general assumptions of field theory and relativity and states that every Hamiltonian that is Lorentz invariant is also invariant under combined application of CPT, even if it is not invariant under C, P and T separately.
  - One of the consequences of this theorem is that particles and anti-particles should have exactly the same mass and lifetime.

- From experiment, it is observed that electromagnetic and strong interactions are symmetric with respect to C, P and T.
- The weak interactions violate C and P separately, but preserve CP and T to a good approximation. Only certain rare processes have been observed to exhibit CP violation.

  - All these observations are consistent with exact CPT symmetry.

# Examples

$$CP\,|\,u\,\rangle = |\,\bar{u}\,\rangle$$

The u quark has $J^P = \frac{1}{2}^+$, so the P operator acting on u has an eigenvalue of +1. The C operator changes particle to antiparticle.

$$CP\,|\,\pi^0\,\rangle = -\,|\,\pi^0\,\rangle$$

The $\pi^0$ has $J^{PC} = 0^{-+}$, so the minus sign comes from the parity operator acting on the $\pi^0$ meson. The C operator changes particle to antiparticle. A $\pi^0$ is its own antiparticle.

$$CP\,|\,\pi^\pm\,\rangle = -\,|\,\pi^\mp\,\rangle$$

The $\pi^\pm$ has $J^P = 0^-$, so the minus sign comes from the parity operator acting on the $\pi$ meson. The C operator changes the particle to antiparticle.

# History of Mixing, CP violation, B factories and Nobel prizes

- **1963:** Cabibbo introduced his angle for the quark mixing with 2 families
- **1964:** Christensen, Cronin, Fitch and Turlay discover CP violation in the $K^0$ system.
- **1967:** A. Sakharov: 3 conditions required to generate a baryon asymmetry:
  - Period of departure from thermal equilibrium in the early universe.
  - Baryon number violation.
  - C and CP violation.

- **1973:** Kobayashi and Maskawa propose 3 generations
- **1980:** Nobel Prize to Cronin and Fitch
- **1981:** I. Bigi and A. Sanda propose measuring CP violation in $B \to J/\psi K^0$ decays.
- **1987:** P. Oddone realizes how to measure CP violation: convert the PEP ring into an asymmetric energy $e^+e^-$ collider.
- **1999:** BaBar and Belle start to take data. By 2001 CP violation has been established (and confirmed) by measuring $\sin 2\beta \neq 0$ in $B \to J/\psi K^0$ decays.
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# Dynamic generation of baryon asymmetry

Suppose equal amounts of matter ( X ) and antimatter ( $\overline{X}$ ):

- X decays to
  - A (baryon number $N_A$) with probability p
  - B (baryon number $N_B$) with probability (1 - p)
- $\overline{X}$ decays to
  - $\overline{A}$ (baryon number $-N_A$) with probability $\overline{p}$
  - $\overline{B}$ (baryon number $-N_B$) with probability $(1 - \overline{p})$
- Generated baryon asymmetry:
  - $\Delta N_{TOT} = N_A p + N_B (1 - p) - N_A \overline{p} - N_B (1 - \overline{p}) = (p - \overline{p}) (N_A - N_B)$
  - $\Delta N_{TOT} \neq 0$ requires $p \neq \overline{p}$ & $N_A \neq N_B$

# CP violation and the baryon asymmetry

We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

$$\frac{n_B - n_B}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$
$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

- The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$
- The mass scale M can be taken to be the electroweak scale O(100 GeV)
- This gives an asymmetry $O(10^{-17})$:

much much below the observed value of $O(10^{-10})$

# We need more CP violation

To create a larger asymmetry, require:

- ▣ new sources of CP violation
  - ▻ that occur at high energy scales

Where might we find it?

- ▣ lepton sector: CP violation in neutrino oscillations
- ▣ quark sector: discrepancies with KM predictions
- ▣ gauge sector, extra dimensions, other new physics:
  - ▻ precision measurements of flavour observables are

generically sensitive to additions to the Standard Model

# Flavour for new physics discoveries

A lesson from history:

FCNC suppressed
$\Delta S=2$ suppressed
wrt $\Delta S=1$

- New physics shows up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z
- Particularly sensitive – loop processes
  - Standard Model contributions suppressed / absent
  - flavour changing neutral currents (rare decays)
  - CP violation
  - lepton flavour / number violation / lepton universality

backup