Particle Physics

Classification of particles

Matter and forces

- 100’s of subatomic particles are known
- Only a few are stable
- We classify them in terms of their properties (mass, spin, parity) and their behaviour re the fundamental interactions (Strong, EM, Weak) e.g lifetimes etc.
- They can’t all be ‘elementary’ i.e. cannot be subdivided into an underlying composite structure
- Eventually, we will link matter and forces in ***The Standard Model*** (Quarks, Leptons, force-carriers ……..)

Hadrons

- Particles which can experience the *Strong Interaction* are members of the Hadron family (Greek: “strong”)
- NB: they can also experience the other interactions
- The Hadron family can be subdivided into two groups Baryons and Mesons
- Baryon: (Greek: “heavy”)
- Meson (Greek: “medium”)

Baryons

- Experience the *Strong Interaction*
- Baryons are fermions
- Baryons are only created in pairs (fermions are created in pairs to conserve Ang. Mom.)
- The proton is the only stable baryon (as far as we know).

$$p, n, \Lambda, \Sigma, \Omega, \Delta, \Xi \cdots$$

- Define a Quantum number called Baryon Number
- Proton has B = +1. Its antiparticle has B = −1

Baryons

- The Baryon Number in an interaction is conserved
- e.g. the *Weak* decay of the neutron

$$n \to p + e^- + \bar{\nu}_e$$

$$B:\ +1 \to +1 + 0 + 0$$

- A proton could not decay to a positron, for example:

$$p \to e^+ + \nu_e$$

$$B:\ +1 \to 0 + 0$$

- Charge conservation is OK (Ang. Mom. isn't)

Mesons

- Experience the *Strong Interaction*
- Mesons are bosons
- Mesons can be created singly
- There are no stable mesons
- Mesons have B = 0. The antiparticle also has B = 0

$$\pi, K, \eta, J/\psi, \rho, \Upsilon \cdots$$

- NB: as we've seen earlier, the muon is NOT a meson (sometimes erroneously referred to as the 'mu-meson').

Particles and Lifetimes

- The strength of the interaction involved in the decay of a particle determines the lifetime of that particle
- As strength ↑, the lifetime ↓

STRONG: $< 10^{-20}$ s

EM: $< 10^{-16}$ s

WEAK: $> 10^{-10}$ s

- (nb, the WEAK decay of the free neutron is unusual ~ 10 min).

Leptons

- Greek: "Light"
- DO NOT experience the *Strong Interaction* (are NOT Hadrons)
- Leptons are fermions (all are spin-1/2)
- Leptons are created in pairs
- There are 3 'generations' of Leptons
- Leptons are fundamental, point-like particles
- Define 3 quantum numbers
  - Electron-Lepton number
  - Muon-Lepton number
  - Tauon-Lepton number

Leptons

- 3 'generations' of Leptons (each 'particle' has an associated neutrino)

$$e^- \quad \& \quad \nu_e$$
$$\mu^- \quad \& \quad \nu_\mu$$
$$\tau^- \quad \& \quad \nu_\tau$$

- Electron-Lepton Number

$$\begin{Bmatrix} e^- \\ \nu_e \end{Bmatrix} \quad L_e = +1 \quad : \quad \begin{Bmatrix} e^+ \\ \overline{\nu}_e \end{Bmatrix} \quad L_e = -1$$

- Similar for muon and tau

Leptons

- Lepton Numbers are conserved

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$
$$L_e: \quad 0 \rightarrow +1 - 1 + 0$$
$$L_\mu: \quad +1 \rightarrow 0 + 0 + 1$$

- Allows one to determine whether a neutrino or an antineutrino is involved

---

Neutrino and Antineutrino

- Same masses (v. small)
- Both are uncharged
- Both are spin-1/2
- Difference is helicity
- Neutrino: direction of angular momentum is opposite to the velocity (Left-hand screw)
- Negative Helicity
- Anti-neutrino: direction of angular momentum is same as the velocity (Right-hand screw)
- Positive Helicity

$$H = \frac{\mathbf{s} \cdot \mathbf{v}}{\mathrm{sv}}$$

Isospin (T)

- 1932 Heisenberg: Another quantum number
- Often called "Isotopic Spin" but has nothing to do with isotopes
- Neutron and proton are both spin-1/2
- n and p masses are approx. equal (difference is ~ 0.14%)
- The Strong interaction is ~ charge independent
- Mirror nuclei have approx. equal binding energies
- Many nuclear properties are independent of whether n or p, once correction for Coulomb effects is made

→ n and p are different charge states of the same particle 'the nucleon"

Isospin (T)

- Define Isospin T.
- There are 2T+1 values of the component T_3
- The number of possible charge states is therefore 2T+1
- e.g. neutron and proton (an "isospin doublet")

$$2T+1=2 \quad \therefore \quad T=\tfrac{1}{2}$$

$$p \Rightarrow \quad T_3=+\tfrac{1}{2}$$

$$n \Rightarrow \quad T_3=-\tfrac{1}{2}$$

Isospin (T)

- e.g. pions (an "isospin triplet")

$$2T+1=3 \quad \therefore \quad T=1$$

$$\pi^+ \Rightarrow \quad T_3=+1$$

$$\pi^0 \Rightarrow \quad T_3=0$$

$$\pi^- \Rightarrow \quad T_3=-1$$

- Isospin is related to charge

Antiparticles

- 1928: Dirac (Nobel 1933)
- Relativistic QM equation of the electron
- Equation had both Positive and Negative energy solutions

$$cf \quad E^2=(pc)^2+(m_0c^2)^2$$

- Positive Solution → Electron
- Negative Solution → predict the anti-Electron ("positron")
- 1932 Anderson : observed the positron in cosmic rays

Antiparticles

- Same mass, spin and lifetime as the particle
- Opposite electric charge (same magnitude)
- Other quantum numbers (e.g. Isospin, Baryon number) are also reversed

$$\bar{T}=T$$

$$\bar{T}_3=-T_3$$

- All particles have an antiparticle
- The π^0 is its own antiparticle ("self-conjugate")
- Pair-production $\gamma \to e^+ + e^-$
- Annihilation $e^+ + e^- \to 2\gamma$

Exclusion Principle

- Two particles:

$$|\psi|^2 = |\psi(n_1,n_2)|^2 = |\psi(n_2,n_1)|^2$$

$$\therefore\quad \psi(n_2,n_1) = \pm\,\psi(n_1,n_2)$$

$$\pm \begin{array}{l} \nearrow \ \text{Bosons}\quad \text{Symmetric} \\ \searrow \ \text{Fermions}\quad \text{Antisymmetric} \end{array}$$

$$\psi = \underset{\downarrow}{f(space)}\cdot g(spin)$$

Orbital motion of particles relative to each other

Interchange particles → factor of $(-1)^l$

Exclusion Principle

$$g(spin) = \begin{cases} \uparrow\uparrow & \text{Symmetric} \\ \uparrow\downarrow & \text{Antisymmetric} \end{cases}$$

e.g. decay of the ρ^0 meson (spin = 1)

$$\text{Consider}\quad \underset{\substack{\nearrow \\ \text{Spin} = 1}}{\rho^0} \to \underset{\substack{\nwarrow\ \nearrow \\ \text{Spin} = 0 \\ \downarrow}}{\pi^0 + \pi^0}$$

$$\therefore\quad l = 1$$

$$g(spin) = \text{symmetric}$$

Exclusion Principle

$$\psi(\pi_2^0,\pi_1^0) = (-1)^l\,\psi(\pi_1^0,\pi_2^0) = -\psi(\pi_1^0,\pi_2^0)$$

i.e. antisymmetric

but

Pions are Bosons
i.e. require symmetric wavefunction

So, decay is not allowed

Observed decay is $\rho^0 \to \underbrace{\pi^+ + \pi^-}$

Distinguishable particles
so no Exclusion Principle restrictions

Strangeness (S)

- 1947 – investigation of cosmic rays

$$\underbrace{\pi^- + p \to V^0}_{\text{STRONG}}\ \underbrace{\to \pi^- + p}_{\text{WEAK}}$$

- The V^0 production is a STRONG interaction
- Its lifetime is ~ 10^{-10} s i.e. a WEAK interaction (a STRONG decay would yield a lifetime of < 10^{-20} s)

$$\pi^- + p \to \cdots \to \pi^- + p$$

- Production looks like the reverse of decay

Strangeness (S)

- 1952: Pais – Brookhaven ‘Cosmotron’: Strange particles produced in pairs (“Associated Production”)

$$\pi^- + p \to \begin{cases} \Lambda^0 + K^0 \\ \\ \Sigma^- + K^+ \end{cases}$$

- 1953: Gell-Mann & Nishijima introduced a new quantum number ‘Strangeness’

$$S(K^0) = +1 \quad \& \quad S(\Lambda^0) = -1$$

$$S(p) = S(n) = 0$$

- ‘Hyperon’ – any baryon with non-zero Strangeness
- Strangeness prevents the ‘strange’ particles decaying by the STRONG interaction

---

Strangeness (S)

- Strangeness is another additive quantum number
- Conserved in STRONG and EM interactions but not in WEAK interaction
- Define ‘Hypercharge’

$$Y = S + B$$

- Gell-Mann & Nishijima:

(1) Assume isospin is conserved in STRONG interaction (i.e. “charge-independent”)

(2) The Λ is only observed as Λ^0

no Λ^+ or Λ^-

$$\therefore \left| T, T_3 \right\rangle = \left| 0,0 \right\rangle$$

Strangeness (S)

(3) $$\pi^- + p \to \Lambda^0 + K^0$$

$$T: \quad 1 \quad + \tfrac{1}{2} \to 0 \quad + \ ?$$

$$\therefore \quad T(K^0) = \tfrac{1}{2} \quad \text{or} \quad \tfrac{3}{2}$$

- If $T(K^0) = \frac{3}{2}$, there should be 4 (2T+1) charge states for Kaons

$$K^-, K^0, K^+, K^{++}$$

hasn’t been observed

$$\therefore \quad T(K^0) = \tfrac{1}{2}$$

$$\begin{Bmatrix} K^+ & T_3 = +\frac{1}{2} \\ K^0 & T_3 = -\frac{1}{2} \end{Bmatrix} \quad : \quad \begin{Bmatrix} \overline{K}^- & T_3 = -\frac{1}{2} \\ \overline{K}^0 & T_3 = +\frac{1}{2} \end{Bmatrix}$$

Strangeness (S)

You can distinguish between K^0 & $\overline{K}^0$

They have different T_3 and S

$$\overline{K}^0 + p \to \Lambda^0 + \pi^+ \qquad \text{YES}$$

$$K^0 + p \to \Lambda^0 + \pi^+ \qquad \text{NO}$$

Hypercharge $Y = S + B$

↓

Gell-Mann, Nishijima equation

$$Q = T_3 + \frac{Y}{2} = T_3 + \frac{S + B}{2}$$

T_3 & Q Conserved in STRONG and EM, not in WEAK

Symmetries

Parity (π)

- Particles have intrinsic parity
- Define nucleons (p, n) to have EVEN (+1) parity
- A multiplicative quantum number

e.g. the STRONG decay of the ϕ meson (spin = 1)

$$\phi^0 \rightarrow K^+ + K^- \qquad \left\{ \pi_\phi = \pi_{K+} \cdot \pi_{K-} \cdot (-1)^l \right\}$$

- Kaons are spin-0 bosons
- Particle/Antiparticle pair

$$\begin{aligned} &\therefore \quad \pi_{K+} = \pi_{K-} \\ &\rightarrow \quad \pi_{K+} \cdot \pi_{K-} = +1 \\ &\therefore \quad \pi_\phi = (-1)^l = -1 \end{aligned}$$

- Conservation of A.M. means $l = 1$

Parity (π)

- Parity is conserved in STRONG and EM interactions but NOT in the WEAK interaction

$$K^+ \rightarrow \begin{cases} \pi^+ + \pi^0 \\ or \\ \pi^+ + \pi^+ + \pi^- \end{cases} \Big\rangle \quad l = 0$$

- Pions have NEGATIVE parity

$$\pi(K^+) = \begin{cases} + \\ - \end{cases}$$

- Whatever the Kaon parity is, it isn't conserved in the WEAK decay

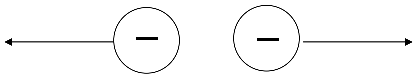
---

Charge Conjugation (C)

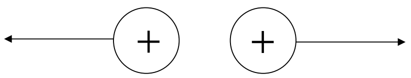
- The Charge Conjugation operator changes a particle into its antiparticle

$$\begin{aligned} C \left| p \right\rangle &= \left| \bar{p} \right\rangle \\ C \left| \pi^+ \right\rangle &= \left| \pi^- \right\rangle \end{aligned}$$

- STRONG and EM interactions are unaffected by Charge Conjugation i.e. "invariant"
- e.g. Coulomb repulsion between 2 electrons



- Apply C-operator $\quad C \left| e^- \right\rangle = \left| e^+ \right\rangle$



Time Reversal (T)

- A collision looks identical with t forwards or backwards

$$^{27}Al\,(p,\alpha)\,^{24}Mg \qquad\qquad ^{24}Mg(\alpha,p)^{27}Al$$

- These reactions are observed to be identical (rates, cross-sections etc)

CPT Invariance Theorem

- All interactions are invariant under the combined action of C, P and T, taken in any order

The τ–θ Puzzle

- Late 1940s: two neutral mesons observed
- Had the same mass, spin etc … seem to be the same particle (neutral Kaon) BUT their decays (lifetimes) were very different

$$\tau \rightarrow \begin{cases} \pi^+ + \pi^0 + \pi^- \\ \quad or \qquad\qquad 5.2\times10^{-8}\ s \quad \rightarrow K^0_{long} \\ 3\pi^0 \end{cases}$$

$$\theta \rightarrow \begin{cases} \pi^+ + \pi^- \\ \quad or \qquad 8.9\times10^{-11}\ s \quad \rightarrow K^0_{short} \\ 2\pi^0 \end{cases}$$

- N.B. This tau particle is NOT the tau lepton.

The τ–θ Puzzle

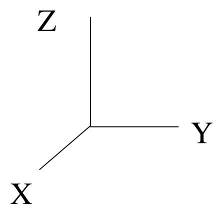
- $\pi^{0,\pm}, \tau, \theta$ are all spin–0
- $\therefore \quad l = 0$ for the τ, θ decay processes
- Parity: pions have ODD (−1) parity

$$\pi_\tau = (-1)^l \cdot \pi_{\pi-} \cdot \pi_{\pi+} \cdot \pi_{\pi 0}$$
$$= (1)(-1)(-1)(-1) = -1$$
$$\pi_\theta = (-1)^l \cdot \pi_{\pi-} \cdot \pi_{\pi+}$$
$$= (1)(-1)(-1) = +1$$

- Different parities but they seem to be the same particle.
- 1956: Lee and Yang: Perhaps they ARE the same particle AND parity is NOT conserved in WEAK interactions ? (Nobel in 1957)

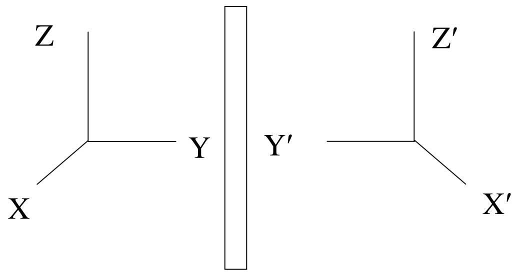
Parity Violation

- No combination of rotations and translations can turn a right-handed frame into a left-handed frame



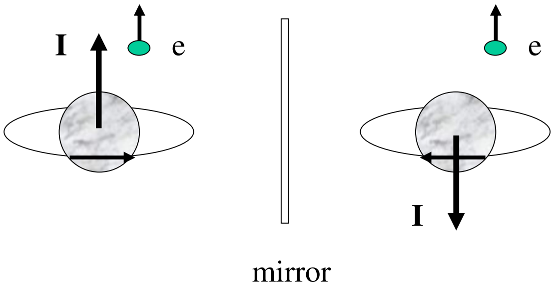
$$\mathbf{x}\times\mathbf{y} = \mathbf{z}$$

- A reflection (mirror) does !



Parity Violation

- If the mirror image of a process is indistinguishable from the process itself, parity is conserved.
- Consider the WEAK decay of a nucleus:



- If Parity is conserved, the two processes must be equally likely i.e. no preferred direction
- Such effects are usually not observed since nuclear spins are randomly aligned

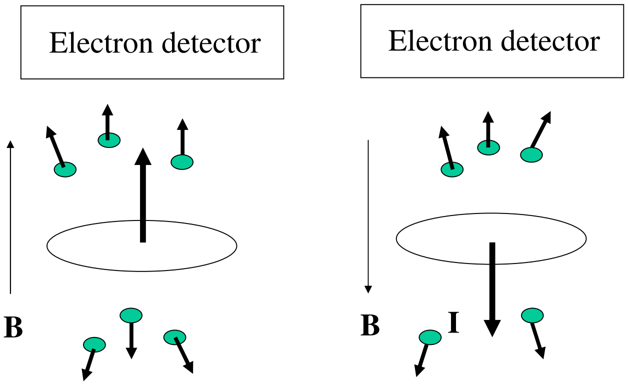
---

Parity Violation

- 1957: Wu and Ambler
- ^{60}Co aligned at 0.01 K in a magnetic field.

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

- Low-T to minimise thermal randomisation effects.
- Count the emitted electrons

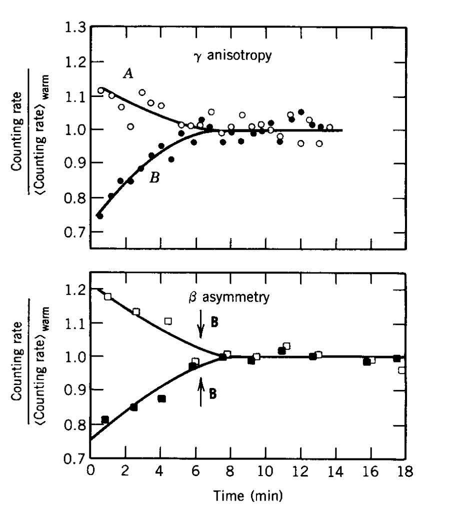


- Reversing the direction of the magnetic field **B** simulates the Parity operation

---

Parity Violation

- A clear preference for electron emission in the opposite direction to the nuclear spin was observed



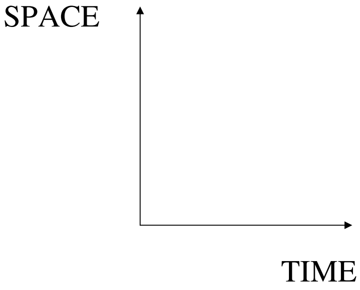
Wu et al.

- Parity is NOT conserved in the WEAK interaction

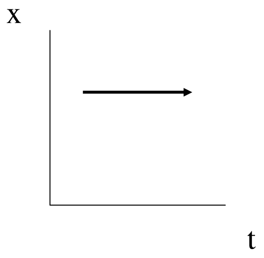
Krane 9.22

Feynman diagrams

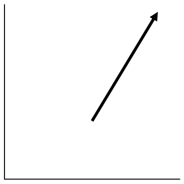
- Richard Feynman (Nobel in 1965)
- A pictorial representation of particle interactions and forces (Quantum Field Theory)
- Powerful calculation methods
- QED, QCD



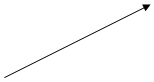
1. A stationary particle



2. A moving particle



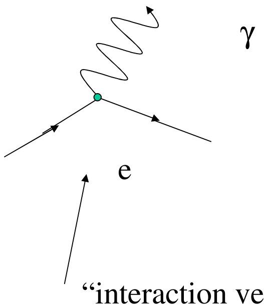
Matter particles



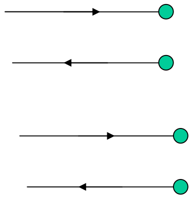
Force carriers

An antiparticle is viewed as a particle travelling backwards in time

e.g. An electron emits a photon and changes direction



“interaction vertex”

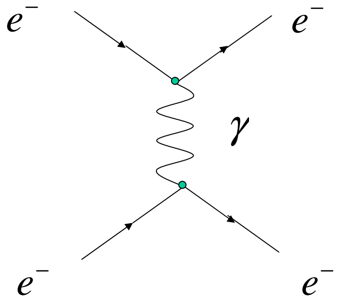


Particle IN OUT

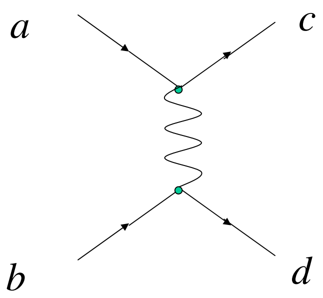
Antiparticle OUT IN

NEVER have a vertex connecting a Lepton to a Quark

Forces between particles are obtained by combining vertices e.g. Coulomb repulsion between electrons



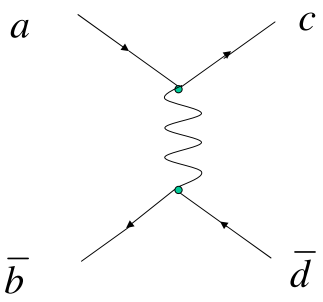
Scattering $a+b \rightarrow c+d$



initial

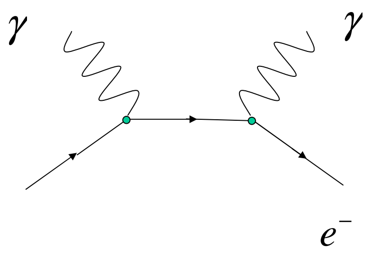
final

Scattering and annihilation $a+\overline{b} \rightarrow c+\overline{d}$

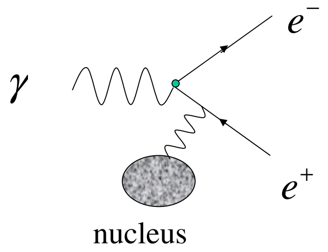


Note arrow directions for antiparticles

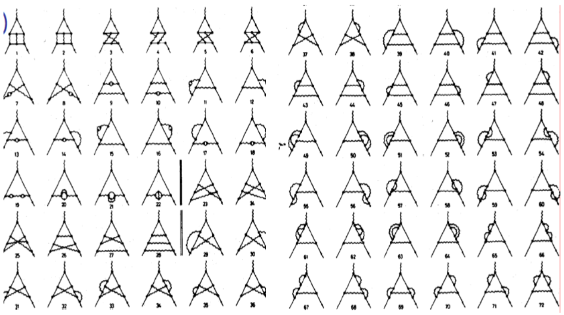
Compton Scattering



Pair production $\gamma \to e^- + e^+$



QED



$$\frac{g_e - 2}{2} = 11596521.869 \pm 0.041 \times 10^{-10}$$ Experiment

$$\frac{g_e - 2}{2} = 11596521.3 \pm 0.3 \times 10^{-10}$$ Theory