Introduction to Elementary Particle Physics

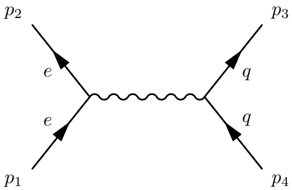
4 (a): Evidence for colour

Dr. Sahal Yacoob

1 September 2020

Colour Charge

Most direct evidence of colour comes from $R \equiv \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)}$.



$\rightarrow$

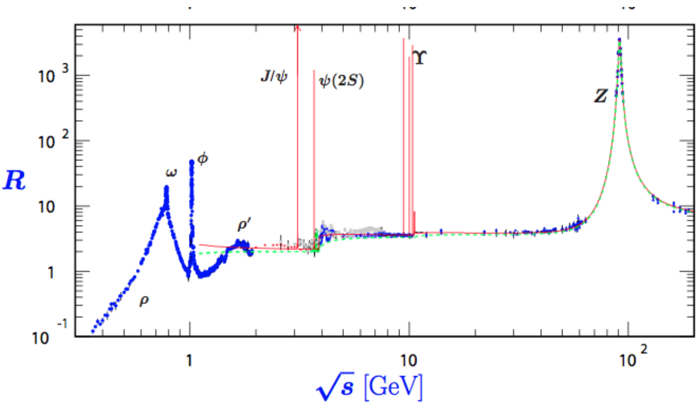
$$\sigma = \frac{\pi}{3}\left(\frac{Q\alpha}{E}\right)^2$$

where Q is the charge in units of e ($\frac{2}{3}$ for u, c, t and $-\frac{1}{3}$ for d, s, b)

- if $E < 2m_q$, quark production is kinematically forbidden
- σ increases when heavier quarks are energetically allowed

If we assume quarks carry 3 colours: $R(E) = 3\sum Q_i^2$

$$R \rightarrow \underbrace{3\left[(\tfrac{2}{3})^2 + 2(-\tfrac{1}{3})^2\right]}_{2 \text{ for } E<2m_c} \rightarrow \underbrace{3\left[2(\tfrac{2}{3})^2 + 2(-\tfrac{1}{3})^2\right]}_{3.33 \text{ for } E<2m_b} \rightarrow \underbrace{3\left[2(\tfrac{2}{3})^2 + 3(-\tfrac{1}{3})^2\right]}_{3.67 \text{ for } E<2m_t}$$



R does not describe hadronic resonances, but:

- the factor of 3 is clearly needed to describe data
- strong evidence of quarks carrying 3 colours

Introduction to Elementary Particle Physics

4 (b): Neutrinos (the little neutral particles)

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The Little Neutral Particle

A quick reminder, or maybe first introduction to neutrinos.

- Neutrino's are very light $0 < m_\nu < 2.3$ eV EM neutral leptons
- They only interact via the weak interaction (no colour charge either)
- They were postulated due to beta decay seemingly exhibiting non conservation in angular momentum and energy.

The Little Neutral Particle – Discovery

- Beta Decay initially thought, and observed to be: $p \to n + e^+$.
  - We now know it is really (at a fundamental level) $u \to d + e^+ + \bar{\nu}_e$.
- Energy Consideration:
  - Consider $p \to n + e^+$ (no neutrino).
  - If the proton and neutron are both at rest then we expect the positron to have a well defined energy $E = m_p - m_n$.
- Angular Momentum Consideration:
  - The angular momentum of a nucleus is integer for an even number of nucleons, and half-integer for an odd number of nucleons (since protons and neutrons have half-integer spin).
  - β-decay doesn't change the number of nucleons, but the electron has spin 1/2. This is an apparent violation of conservation of spin / angular momentum.

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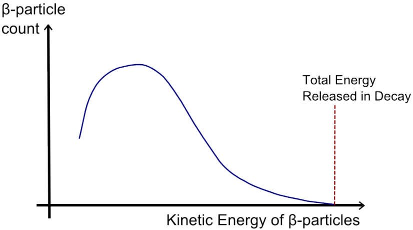


Solar Neutrino Problem

The pp Chain

Step 1: Two protons make a deuteron

$$p + p \rightarrow d + e^+ + \nu_e$$
$$p + p + e^- \rightarrow d + \nu_e$$

Step 2: Deuteron plus proton makes ^{3}He.

$$d + p \rightarrow {}^3\mathrm{He} + \gamma$$

Step 3: Helium-3 makes alpha particle or ^{7}Be.

$$^3\mathrm{He} + p \rightarrow \alpha + e^+ + \nu_e$$
$$^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \alpha + p + p$$
$$^3\mathrm{He} + \alpha \rightarrow {}^7\mathrm{Be} + \gamma$$

Step 4: Berillium makes alpha particles.

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$
$$^7\mathrm{Li} + p \rightarrow \alpha + \alpha$$
$$^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$$
$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$$
$$^8\mathrm{Be}^* \rightarrow \alpha + \alpha$$

many ν_e's created

Ray Davies, Homestake mine, 1968

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e$$

solar ν_e flux is 1/3 of predicted value

Neutrino Mixing

Experimental limits on neutrino mass: $0 \leq m_{\bar{\nu}_e} < 2.3\,eV$

If $m_\nu > 0$, *neutrino mixing* is possible, in which case

flavour eigenstates:

$$(\nu_e,\ \nu_\mu,\ \nu_\tau)$$

- definite coupling to e, μ, τ
- indefinite masses

mass eigenstates:

$$(\nu_1,\ \nu_2,\ \nu_3)$$

- definite masses m_1, m_2, m_3
- indefinite coupling to e, μ, τ

Therefore, a neutrino would be a quantum mixing of the mass and flavour eigenstates. Neutrinos would therefore

- *interact* as flavour eigenstates
- *propagate* as mass eigenstates

Neutrino Oscillations

Consider the case with just two neutrino species, with flavour eigenstates (ν_e, ν_μ) and mass eigenstates (ν_1, ν_2).

$$\begin{aligned} \nu_e &= \quad \nu_1 \cos\theta_{12} + \nu_2 \sin\theta_{12} \\ \nu_\mu &= -\nu_1 \sin\theta_{12} + \nu_2 \cos\theta_{12} \end{aligned}$$

- using $\sin$ and $\cos$ just helps the normalization
- the *mixing angle*, θ_{12} must be determined experimentally

If we start with a pure ν_e state with momentum $\mathbf{p}$,

$$|\nu_e, \mathbf{p}\rangle = |\nu_1, \mathbf{p}\rangle \cos\theta_{12} + |\nu_2, \mathbf{p}\rangle \sin\theta_{12}$$

let it evolve for time t, note that ν_1 and ν_2 are the mass eigenstates

$$|\nu_e, \mathbf{p}\rangle \to e^{-iE_1 t/\hbar} |\nu_1, \mathbf{p}\rangle \cos\theta_{12} + e^{-iE_2 t/\hbar} |\nu_2, \mathbf{p}\rangle \sin\theta_{12}$$

So the neutrino is no longer a pure ν_e state, The evolved state can be written

$$A(t)\,|\nu_e, \mathbf{p}\rangle + B(t)\,|\nu_\mu, \mathbf{p}\rangle$$

where

$$A(t) = e^{-iE_1 t/\hbar}\cos^2\theta_{12} + e^{-iE_2 t/\hbar}\sin^2\theta_{12} \qquad B(t) = \sin\theta_{12}\cos\theta_{12}\left[e^{-iE_1 t/\hbar} - e^{-iE_2 t/\hbar}\right]$$

So the probability of finding a ν_β state is

$$P(\nu_e \to \nu_\mu) = |B(t)|^2 = \sin^2(2\theta_{12})\,\sin^2\left[\frac{(E_2 - E_1)t}{2\hbar}\right]$$

Therefore, if $\theta_{12} \neq 0$ and $m_1 \neq m_2$ (which would mean that $E_1 \neq E_2$ because $\mathbf{p}$ is defined) then the neutrino flavour will oscillate. If $m_1 = m_2 = 0$ oscillations are not possible.

Using $E_{i,j} \gg m_{i,j}$, and $t \approx L/c$,

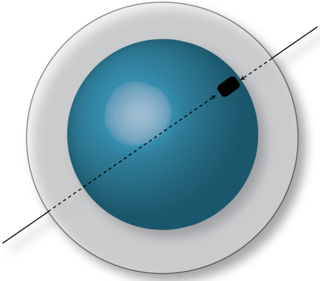
$$P(\nu_e \to \nu_\mu) \approx \sin^2(2\theta_{12})\,\sin^2(L/L_0) \quad \text{with} \quad L_0 = \frac{4E(\hbar c)}{(m_2^2 - m_1^2)(c^4)}$$

Atmospheric Muon Neutrinos

Cosmic ray protons hitting the atmosphere produce pions ($\pi^{\pm}$).

- $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu_\mu}$
- $\pi^- \to \mu^- + \bar{\nu_\mu} \to e^- + \bar{\nu_e} + \nu_\mu$

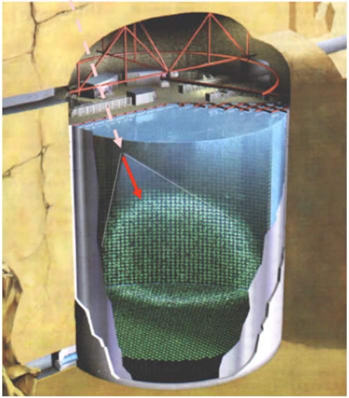
This suggests the muon to electron neutrino ratio should be 2 to 1.

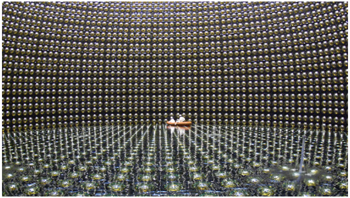


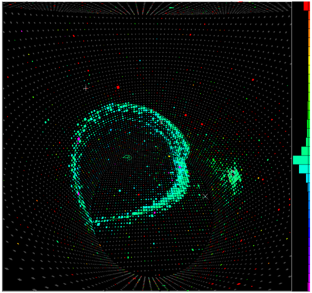
- cosmic proton flux is isotropic
- place detector near surface of earth
- observe the muon to electron neutrino ratio coming above vs below
- no oscillations: expect 2:1 above, 2:1 below
- oscillations: expect 2:1 above, $\sim$?:1 below

Evidence for Neutrino Oscillations

Super-Kamiokande (1998)







Observed 2:1 above and ~1:1 below, so neutrino oscillation hypothesis supported. Some recent Super-K news here

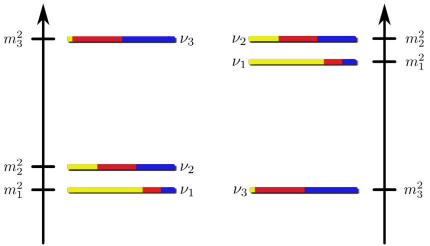
Neutrino Oscillation Parameters

Neutrino beam-line experiments confirm the oscillation and measure neutrino oscillation parameters.
Oscillation length, L_0, depends on squared mass difference:

$$\Delta(m_{12}^2) \equiv m_1^2 - m_2^2$$

Experimental values yield

$$1.9 \times 10^{-3} \lesssim \Delta(m_{32}^2) \lesssim 3.0 \times 10^{-3}\, eV^2, \quad \text{and} \quad \sin^2(2\theta_{23}) \gtrsim 0.9$$
$$7.6 \times 10^{-5} \lesssim \Delta(m_{21}^2) \lesssim 8.6 \times 10^{-5}\, eV^2, \quad \text{and} \quad 0.32 \lesssim \tan^2(\theta_{12}) \lesssim 0.48$$



- mass hierarchy is not known
- could be 'normal' or 'inverted'
- ν_e, ν_μ, ν_τ

Solving the solar Neutrino Problem

The Sudbury Neutrino Observatory[1] definitively established that neutrinos change flavour, and therefore must have mass.

CC Charged Current Reaction	$\upsilon_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4 MeV$
NC Neutral Current Reaction	$\upsilon_x + d \rightarrow \upsilon_x + p + n$	$E_{threshold} = 2.2 MeV$
ES Elastic Scattering Reaction	$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$	$E_{threshold} \approx 0$

x denotes that this reaction will take place with any neutrino.

[1] https://arxiv.org/abs/1602.02469

Unification

Maxwell unified electricity and magnetism into *electromagnetism*

Glashow, Weinberg, and Salam (GSW) unified electromagnetism and weak forces, called *electroweak* (EWK). The *Higgs boson* is a prediction of EWK theory.

A *Grand Unified Theory* (GUT) would combine EWK and QCD, but so far there is no experimental evidence for a GUT.

Unification of gravity with a GUT is the ultimate unification. *String theory* is currently the most promising approach - but far from experimentally testable.

Questions Beyond the Standard Model

Grand Unification

Why is there no antimatter in the universe?

What is Dark Matter/Energy?