PARTICLE PHYSICS

1) - Study of MATTER (the most fundamental elements that constitute the observable world) and FORCES (the most basic interactions between elements of matter) current understanding embodied in the 'STANDARD MODEL'.

MATTER - consists of leptons and quarks (which form Hadrons).

leptons e ν_e, μ ν_μ, τ ν_τ (spin $\frac{1}{2}$) - charged particle and neutrino.

Hadrons (consist of $\frac{1}{2}$ integer spin quarks) - Baryons $S = \frac{1}{2}\mathbb{Z}'$ 3 quarks; Mesons (quark, antiquark) $S = \text{Int } \mathbb{Z}$.

No free quarks CONFINEMENT within Hadrons

Flavour $\rightarrow$ u d c s t b come in 3 COLOURS

FORCES are due to exchange of elementary particles GAUGE BOSONS

EM	photon	γ
WEAK	$W^\pm, Z^0$	
STRONG	gluon	g

These are massive so only occur at certain energies + Higgs for gravity (yet to be discovered).

* All particles have ANTIPARTICLES. identical apart from sign interaction. (i.e. charge - positron e^+, electron e^-).

Forces have 'Yukawa' form $F_i = \alpha_i \hbar c \left(\frac{1}{r^2} + \frac{m_i}{r}\right) e^{-m_i r/\hbar c}$ for type of interaction i at a distance r via exchange of a gauge boson of mass m_i.

nuclear decay can be modelled by $m_i = m_{pion}$ $p \xrightarrow{\pi^0} p$

for EM, STRONG $m_i = 0$ $\alpha_{EM} \sim \frac{1}{137}$ $\alpha_S \sim 1$. $m_{W^\pm} \sim 80.4\ \text{GeV}/c^2$ $m_{Z^0} \sim 91.2\ \text{GeV}/c^2$ $\alpha_W \sim \frac{1}{29}$

* Study particle physics using (i) Static properties {mass, spin, magnetic moments, parity} (ii) Particle scattering cross section $\sigma = \Gamma_{i\to f}/\text{flux}$ $\Gamma_{i\to f} = \frac{2\pi}{\hbar}|M_{if}|^2 g(E)$ F.G.R. and $d\sigma/d\Omega$. (iii) Decays $N(t) = N_0 e^{-t/\tau}$

use theory to predict angular dependence of $|M_{if}|^2$

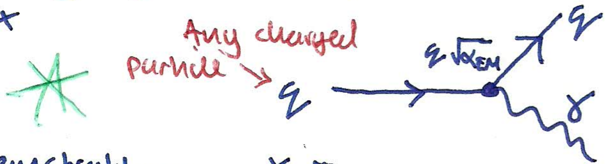
Total decay rate $\equiv$ 'Total width' $\Gamma = \hbar/\tau$

Partial width $\Gamma_i \Rightarrow \Gamma = \sum_i \Gamma_i$ Branching ratio $B_i = \Gamma_i/\Gamma$

$i \Rightarrow$ decay mode i.

* Feynmann diagrams allows one to compute matrix elements for a particular interaction between particles. Represents a sum over all time orderings. frame independent. Add matrix elements for all possible Feynmann diagrams then $|\ |^2$ to get $\Gamma_{i\to f} \frac{\hbar}{2\pi g(E)}$.

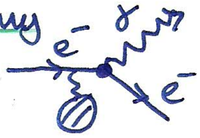
2) QED - concern the EM interaction via exchange of photons (virtual usually i.e. they have imaginary momentum). Generate all Feynmann diagrams from BASIC EM VERTEX



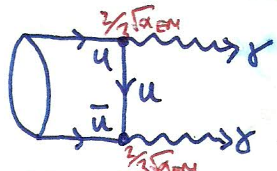
M for this diagram $\simeq q\sqrt{\alpha_{EM}}$ - Vertex factor. If propagator effects are ignored matrix elements are Π vertex factors. q = charge/e.

and h.s.r in diagram e.g.

i.e. Bremsstrahlung $e^- \to e^-\gamma$ $\Gamma \propto \frac{1}{137}$



Decay $\pi^0 \to \gamma\gamma$



$q(u) = +\frac{2}{3}$

$\Gamma \propto \left|\frac{2}{3}\frac{1}{\sqrt{137}}\ \frac{2}{3}\frac{1}{\sqrt{137}}\right|^2$

* Energy, momentum, (linear, angular) charge must be conserved at each vertex.

Note #leptons - #antileptons is conserved [LEPTON # CONSERVATION] as well as #Quarks - #antiquarks [BARYON # CONSERVATION] i.e. $\mu^- \not\to e^-\gamma$ $p \not\to e^+\gamma$

3) Gauge Theories describe the interaction of particle wavefunctions ensuring that the physics remains invariant under certain SYMMETRY transformations which reflect CONSERVATION LAWS observed in nature.

SYMMETRY operator $\Rightarrow$ existence of UNITARY OPERATOR $\hat{U}$ if $\psi(\underline{r},t)$ is an eigenstate of Hamiltonian $\hat{H}$ then so is $\psi'(\underline{r},t) = \hat{U}\psi(\underline{r},t)$ and $[\hat{U},\hat{H}] = 0$

E.g. translational invariance $\psi'(x,t) = \psi(x+\varepsilon,t) = \psi(x,t) + \varepsilon\frac{d}{dx}\psi(x,t) + \ldots\ldots$

let $\hat{U} = 1 + \varepsilon\frac{d}{dx} = \hat{1} + \frac{i}{\hbar}\varepsilon\hat{P}_x$ $(\underline{P} = \frac{\hbar}{i}\nabla)$ Now since $[\hat{U},\hat{H}] = 0 \Rightarrow [\hat{P}_x, \hat{H}] = 0$

$\Rightarrow$ MOMENTUM CONSERVED. consider unitary operator $\hat{U} = e^{iq\cdot\alpha}$ if $\alpha(\underline{r},t)$ varies in spacetime $\to$ acts like a field. Local transformation $\psi' = e^{iq\alpha}\psi$ changes phase (not $|\psi|^2$) of all particles depending on their position $\to$ require a physical field to undo these changes. i.e photon field for EM.

.... e.g. for E.M. S.E is $\left[\frac{1}{2m}(-i\nabla - q\underline{A})^2 + q\phi\right]\psi = i\frac{\partial\psi}{\partial t}$ vector potential $A = (\phi, \underline{A})$

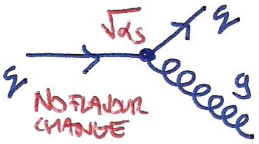
Now $\underline{A} \to \underline{A} + \nabla\alpha$, $\phi \to \phi - \frac{\partial\alpha}{\partial t}$ does not alter $\underline{E} = -\nabla\phi - \frac{\partial\underline{A}}{\partial t}$, $\underline{B} = \nabla\times\underline{A}$ which characterise the physics of E.M.

LOCAL GAUGE INVARIANCE

Turns out $\psi \to e^{iq\alpha}\psi$ allows for these transforms so ⇒ photon field must exist.

4) QCD - Quantum chromodynamics is the theory of the strong interaction.

BASIC VERTEX



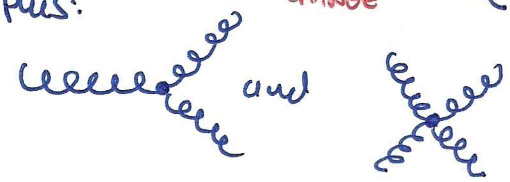
gluons assumed to be massless spin 1 quanta carrying COLOUR quantum number

3 colours + 3 anticolours.
r g b (carried by antiquarks)

Real gluons are orthogonal linear combinations of colour states $r\bar{b}, r\bar{g}, b\bar{r}, b\bar{g}, g\bar{r}, g\bar{b}, r\bar{r}, b\bar{b}, g\bar{g}$.

Note $r\bar{r} + b\bar{b} + g\bar{g}$ has no 'net colour' ∴ plays no part in strong interaction. Hence 8 coloured gluons.

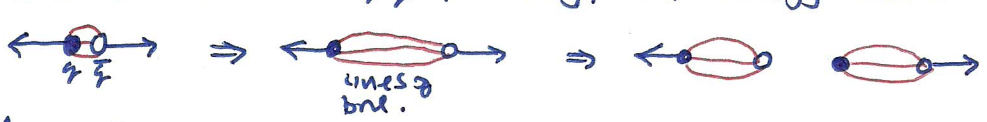
plus:



→ could make a colourless state (Glueball) out of gluons. Not observed yet.

* Quarks and gluons are permanently confined inside Hadrons.

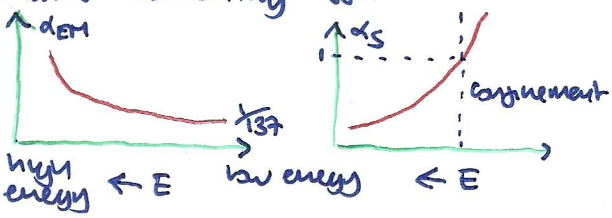
Self interaction of gluons between them squeezes lines of force into tube-like regions. ⇒ Energy / unit length stored in field ~ constant ⇒ separation energy → ∞. If one tries to separate quarks in a $q\bar{q}$ pair (e.g) this energy creates new pairs - HADRONISATION.



- Get jets of hadrons in a $q\bar{q}$ separation event.

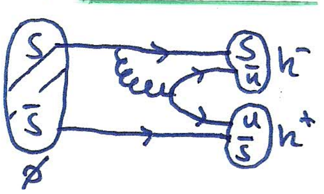
* Asymptotic freedom. In QED +ve charges are screened by -ve charges. At small distances (⇒ high energy probing particle) - smaller screening effect - larger effective charge - large effective value of α_{EM}

Analogous effect in QCD - "colour screening" except due to gluon self interaction effect is opposite. Gluons appear 'free' at high energies i.e. α_s decreases.



* Scattering - as in QED with Feynman rules for calculating matrix elements.

e.g. $\phi \to K^+K^-$



NOTE: PARITY CONSERVED IN EM, STRONG INTERACTIONS (can be violated in WEAK interactions) - useful diagnostic. Note whether bosons or fermions are produced ⇒ even if parity conserved the wrong sign can mean interaction not possible e.g. $\omega^0 \not\to \pi^0\pi^0$ — if produce same particle P = -1 ⇒ Fermions, P = 1 ⇒ Bosons.

* Evidence for colour. Consider ratio $R = \sigma(e^+e^- \to \text{Hadrons}) / \sigma(e^+e^- \to \mu^+\mu^-)$

i.e. QED interaction. i.e

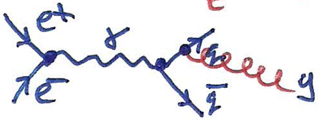
Expect $R = 3\sum_i q_i^2$ for quark colour charge q. (Note each event is independent so add $|M|^2$). ×3 due to 3 colours. ∴ sum depends on energy of e^+e^- collision. As raise energy expect to see steps as more quarks can be created.

$E > 2m_s$ $R = 3(\underset{u}{\frac{4}{9}} + \underset{d}{\frac{1}{9}} + \underset{s}{\frac{1}{9}}) = 2$ $E > 2m_c$ $R = 3(\ldots + \underset{c}{\frac{4}{9}}) = 3\frac{1}{3}$ $E > 2m_b$ $R = 3(\ldots + \underset{b}{\frac{1}{9}}) = 3\frac{2}{3}$

$E > 2m_t$ $R = 3(\ldots + \underset{t}{\frac{4}{9}}) = 5$

* Evidence for gluons. Quarks can radiate gluons like electrons can radiate photons.

e.g.



- Extra α_s in cross section. Experimentally observe 3 Hadronic jets - angle depends on gluon spin (=1)

Triple Gluon vertex is lowest energy gluon radiation → modifies angular distribution.

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* **Hadron Masses** Mass differences amongst hadrons are partly due to differences in quark masses and partly due to the spin-spin interaction of confined quarks.

c.f. Hyperfine splitting in H_2 $(l=0)$ in QED: $\Delta E \propto \frac{\underline{S}_p \cdot \underline{S}_e}{m_p m_e}$

MESON MASSES $q_1 q_2$, A_m constant. $M_m = m_1 + m_2 + A_m \frac{\underline{S}_1 \cdot \underline{S}_2}{m_1 m_2}$

Note all quarks are spin $\frac{1}{2}$ so $S_i^2 = \frac{1}{2}(\frac{1}{2}+1) = \frac{3}{4}$

Now $\underline{S}_1 \cdot \underline{S}_2 = \frac{1}{2}(S^2 - S_1^2 - S_2^2)$ where $\underline{S} = \underline{S}_1 + \underline{S}_2$ so:

0^- MESONS $M_m = m_1 + m_2 - \frac{3A_m}{4m_1 m_2}$

1^- MESONS $M_m = m_1 + m_2 + \frac{A}{4m_1 m_2}$

BARYON MASSES $q_1 q_2 q_3$, A_B constant

$M_m = m_1 + m_2 + m_3 + A_B \left[\frac{\underline{S}_1 \cdot \underline{S}_2}{m_1 m_2} + \frac{\underline{S}_1 \cdot \underline{S}_3}{m_1 m_3} + \frac{\underline{S}_2 \cdot \underline{S}_3}{m_2 m_3}\right]$

use $\underline{S}_1 \cdot \underline{S}_2$ above again....

* **Baryon magnetic moments** If all the quarks have zero orbital angular momentum

$\underline{\mu}_{Baryon} = \underline{\mu}_1 + \underline{\mu}_2 + \underline{\mu}_3$ Now for pointlike spin $\frac{1}{2}$ particle of charge q $\underline{\mu} = \frac{q}{m}\underline{S}$

So $\langle \uparrow | \mu | \uparrow \rangle = \frac{q}{m}\frac{\hbar}{2}$. $\therefore \langle \uparrow | \underline{\mu}_{Baryon} | \uparrow \rangle = \frac{e\hbar}{2}\left(\frac{q_1}{m_1} + \frac{q_2}{m_2} + \frac{q_3}{m_3}\right)$

actually state $|\uparrow_1 \uparrow_2 \uparrow_3\rangle$

* **Hadron Resonances** - Most hadronic states decay via the strong interaction $\Rightarrow$ short lifetimes. Identify state by peak in cross section vs. energy. i.e. Breit Wigner.

$\sigma(X+Y \to Z \to A+B) = \frac{\pi \lambda\!\!\!^{-2} g \Gamma_{XY} \Gamma_{AB}}{(E_0 - E)^2 + \Gamma^2/4}$

$g = \frac{2J_Z + 1}{(2S_X+1)(2S_Y+1)}$

For hadron Z of energy E_0

$\Gamma_{XY} = \Gamma(Z \to X+Y)$ $\Gamma_{AB} = \Gamma(Z \to A+B)$

$\lambda\!\!\!^- = \hbar / p_X^*$ momentum in c.o.m system.

5) **Relativistic Wave Equations** Generate (non-relativistic) S.E via replacing E, p in energy expression by Q.M. operators $E \to i\hbar\frac{\partial}{\partial t}$ $p \to \frac{\hbar}{i}\nabla$

i.e. $E = \frac{p^2}{2m} + V \to i\hbar\frac{\partial}{\partial t}\psi = \frac{-\hbar^2}{2m}\nabla^2\psi + V\psi$ S.E. Now using special relativity $E^2 = p^2c^2 + m^2c^4 \Rightarrow -\hbar^2\frac{\partial^2\psi}{\partial t^2} = -c^2\hbar^2\nabla^2\psi + m^2c^4 \Rightarrow \nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi = \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2}$

This is the KLEIN GORDON equation. Solutions are of the form

$\psi(\underline{r}, t) = Ae^{-i(Et - \underline{p}\cdot\underline{r})/\hbar}$ Note $E = \pm c\sqrt{p^2 + m^2c^2}$ i.e. -ve / +ve Energy Solutions

↳ interpret as { Particles -ve E / Antiparticles +ve E } K.G. equation not much use since probability of finding a particle is not conserved........ Though can use it as a foundation to generating Weyl and Dirac equations.

* **The Dirac Equation** $\Rightarrow$ Aim to factorise K.G. equation $\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{m^2c^2}{\hbar^2}\right)\psi = 0$

$\Rightarrow \left(i\gamma^1\frac{\partial}{\partial x} + i\gamma^2\frac{\partial}{\partial y} + i\gamma^3\frac{\partial}{\partial z} + \frac{i\gamma^0}{c}\frac{\partial}{\partial t} + \frac{mc}{\hbar}\right)\left(i\gamma^1\frac{\partial}{\partial x} + i\gamma^2\frac{\partial}{\partial y} + i\gamma^3\frac{\partial}{\partial z} + \frac{i\gamma^0}{c}\frac{\partial}{\partial t} - \frac{mc}{\hbar}\right) = 0$

γ's must anticommute to remove cross terms. 4 γ's $\Rightarrow$ 4×4 matrices.

DIRAC eq is $i\left(\frac{1}{c}\underline{\underline{\gamma}}^0\frac{\partial}{\partial t} + \underline{\underline{\gamma}}^1\frac{\partial}{\partial x} + \underline{\underline{\gamma}}^2\frac{\partial}{\partial y} + \underline{\underline{\gamma}}^3\frac{\partial}{\partial z}\right)\psi - \frac{mc}{\hbar}\psi = 0$ ψ are 4 component SPINORS

$\underline{\underline{\gamma}}^0 = \begin{pmatrix} 1&0&0&0 \\ 0&1&0&0 \\ 0&0&-1&0 \\ 0&0&0&-1 \end{pmatrix}$ $\underline{\underline{\gamma}}^1 = \begin{pmatrix} 0&0&0&1 \\ 0&0&1&0 \\ 0&-1&0&0 \\ -1&0&0&0 \end{pmatrix}$ $\underline{\underline{\gamma}}^2 = \begin{pmatrix} 0&0&0&-i \\ 0&0&i&0 \\ 0&i&0&0 \\ -i&0&0&0 \end{pmatrix}$ $\underline{\underline{\gamma}}^3 = \begin{pmatrix} 0&0&1&0 \\ 0&0&0&-1 \\ -1&0&0&0 \\ 0&1&0&0 \end{pmatrix}$

$= \begin{pmatrix} \underline{\underline{1}} & 0 \\ 0 & -\underline{\underline{1}} \end{pmatrix}$ $= \begin{pmatrix} 0 & \underline{\underline{\sigma}}_x \\ -\underline{\underline{\sigma}}_x & 0 \end{pmatrix}$ $= \begin{pmatrix} 0 & \underline{\underline{\sigma}}_y \\ -\underline{\underline{\sigma}}_y & 0 \end{pmatrix}$ $= \begin{pmatrix} 0 & \underline{\underline{\sigma}}_z \\ -\underline{\underline{\sigma}}_z & 0 \end{pmatrix}$ using Pauli Spin matrices.

↳ get correct spin eigenstates when solving Dirac equation for $\underline{p} = 0$

i.e. $i\underline{\underline{\gamma}}^0\frac{\partial\psi}{\partial t} - \frac{mc^2\psi}{\hbar} = 0 \Rightarrow \psi = \begin{pmatrix} \exp(-mc^2t/\hbar) \\ " \\ \exp(mc^2t/\hbar) \\ " \end{pmatrix}$ Particles / antiparticles

Define Spin operator $\underline{S} = \begin{pmatrix} \underline{\underline{\sigma}} & 0 \\ 0 & \underline{\underline{\sigma}} \end{pmatrix}\hbar/2$

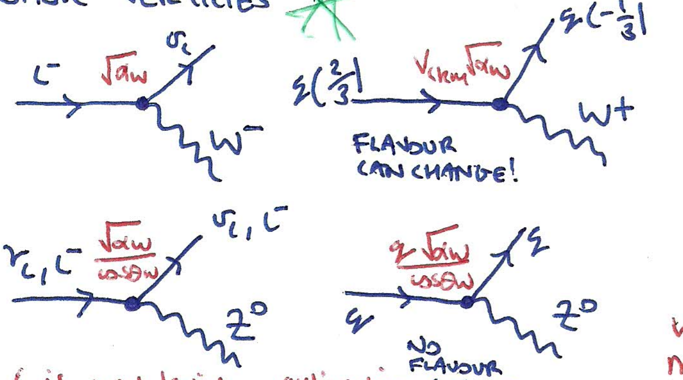
$$\Rightarrow \quad \underline{\underline{S}}_z \psi = \frac{\hbar}{2} \begin{pmatrix} \exp(-imc^2t/\hbar) \\ " \\ -\exp(-imc^2t/\hbar) \\ " \end{pmatrix}$$ ← particle, spin up / " spin down / ← antiparticle spin up / " spin down

For solutions $\underline{p} \neq 0$
Try $\psi = \underline{u}\, e^{-i(Et - \underline{p}\cdot\underline{r})/\hbar}$
where $E = c\sqrt{p^2+m^2c^2}$ for u_1, u_2; $-c\sqrt{p^2+m^2c^2}$ for u_3, u_4.

- Equipped with Dirac equation one can calculate matrix elements properly from Feynmann Diagrams. (using Feynmann rules not discussed here).

6) Weak interactions. Fermi theory of β decay fails at high energies (Diverges) (Sargent rule for leptonic decay $\Gamma_x = \frac{G_F^2 m_x^5}{192\pi^3}$ $G_F = 1.166\times10^{-5}\ \mathrm{GeV}^{-2}$).

BASIC VERTICIES



l is any lepton ($+$ pairs with $\bar{\nu}_l$ — antineutrino)

$\alpha_W \sim \frac{1}{29}$

$$\underline{\underline{V}}_{CKM} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

← parameterises couplings constants between W^+ decaying quark states

$\lambda = \sin\theta_C$
$\theta_C \simeq 13^\circ$
$\theta_W \simeq 29^\circ$
constants that go into the standard model.

$W^\pm, Z^0$ are massive so can only exist above threshold energies.

Weak interactions allow parity violation (unlike EM and strong). Reason? vertex factor for weak interactions includes a term $\propto \frac{1}{2}(1-\gamma^5)$ which acts as the 'HELICITY' operator i.e. selects left handed particles (and right handed antiparticles) ONLY at high energy. Left handedness for particles $\Rightarrow$ $\underline{S}$ is antiparallel to $\underline{p}$.

* Z^0 decays - why there are only 3 types of neutrino
- measure total width for $Z^0 \rightarrow \ldots\ldots$ decay, Γ_{Z^0}. Now since all Z^0 $\rightarrow$ leptons and $Z^0 \rightarrow$ quarks (well hadrons) have the same decay rates can write

$$\Gamma_{Z^0} = 3\Gamma_{ee^+} + 3\Gamma_{u\bar{u}} + 3\Gamma_{d\bar{d}} + N_\nu \Gamma_{\nu\bar{\nu}} = 3\Gamma_{ee^+} + 15\Gamma_{d\bar{d}} + N_\nu\Gamma_{\nu\bar{\nu}}$$

($N_\nu\Gamma_{\nu\bar{\nu}}$ is an 'invisible' partial width which is found by experimentally measuring $\Gamma_{Z^0}, \Gamma_{ee^+}, \Gamma_{d\bar{d}}$ etc. Using theory for $\Gamma_{\nu\bar{\nu}}$ one can work out N_ν)

$$\Rightarrow N_\nu \simeq \frac{\Gamma_{Z^0} - 3\Gamma_{ee^+} - 15\Gamma_{d\bar{d}}}{\Gamma_{\nu\bar{\nu}}}$$

Turns out $N_\nu \approx 3$.

7) Beyond the Standard Model

Successes: Describes all existing particle physics data to extreme accuracy

Problems: lots of free parameters (~ 20) i.e. masses of leptons, quarks, couplings $\alpha_{EM}, \alpha_S, \alpha_W$, θ_W, θ_C, quark and lepton charges, mixing (V_{CKM}); Gravity not included.

* Higgs Boson H^0 (neutral spin 0 boson) thought to give particles mass via their interaction with the Higgs field (consisting of quanta called Higgs Bosons!)
New possible vertices depending on Higgs mass. i.e. $H^0 \rightarrow 2Z^0 \rightarrow 2\mu^+\mu^-$ or $H^0 \rightarrow 2\gamma$.

* Neutrino oscillations ν_e, ν_μ, ν_τ can oscillate i.e. ν_e can become ν_τ spontaneously over time! Explains odd results observed at SUPERKAMIOKANDE which detects arrival rates of atmospheric/solar muon and electron neutrinos. (uses CHERENKOV radiation - light emitted when charged particle exceeds $\frac{c}{n}$ in a medium). use

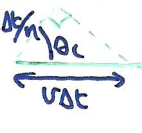
$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

θ mixing angle
↑ lepton # e-states
↑ mass eigenstates

and $\nu_{1,2}(t) = \nu_{1,2}(0)e^{-iE_{1,2}t/\hbar}$ to yield

$$\left|\frac{\nu_e(t)}{\nu_e(0)}\right|^2 = 1 - \sin^2 2\theta \sin^2\left[\frac{(E_1-E_2)t}{2\hbar}\right]$$

as a model for N. oscillations



$\cos\theta_c = \frac{c}{n\nu}$ θ_c real $\Rightarrow \nu$ when $\frac{c}{n\nu} < 1$ $\Rightarrow \nu > \frac{c}{n}$

$1\,b = 10^{-28}\,m^2$

cross section units are often in BARNS (b)

V.Gibson
Lent 2000

PARTICLE PROPERTIES

From the *Review of Particle Physics*, European Physical Journal **C3** (1998)

Parity:

Quark and charged leptons P = +1

Antiquarks and antileptons P = −1

Parity of 2 particles with A.M l is

$P = P_1 P_2 (-1)^l$

Quarks (spin 1/2)

Name	Flavour	Mass (GeV/c²)	Charge (e)
up	u	≈ 0.35	$+2/3$
down	d	$m_d \approx m_u$	$-1/3$
charm	c	1.5	$+2/3$
strange	s	0.5	$-1/3$
top	t	$174(\pm5)$	$+2/3$
bottom	b	4.5	$-1/3$

Leptons (spin 1/2)

Lepton	Charge	Mass (MeV/c²)	Mean life (s)	Lepton Decay Mode	Branching Ratio (%)
ν_e	0	$< 15\,\mathrm{eV/c^2}$	stable		
ν_μ	0	< 0.17	stable		
ν_τ	0	< 18.2	stable		
e	±1	0.511^a	stable		
μ	±1	105.658^b	$2.197 \times 10^{-6^c}$	$e^-\bar{\nu}_e\nu_\mu$	≈ 100
τ	±1	$1777.0(\pm3)$	$290.0(\pm12) \times 10^{-15}$	$\mu^-\bar{\nu}_\mu\nu_\tau$	$17.37(\pm9)$
				$e^-\bar{\nu}_e\nu_\tau$	$17.81(\pm7)$
				hadrons $+\nu_\tau$	≈ 65

[a] The error on the e mass is $1.5 \times 10^{-7}\,\mathrm{MeV/c^2}$.
[b] The error on the μ mass is $3.4 \times 10^{-5}\,\mathrm{MeV/c^2}$.
[c] The error on the μ lifetime is 4×10^{-11} s.

N.B. Numbers given in brackets correspond to the error in the last digit.
For example, $m_\tau = 1777.0(\pm3)\mathrm{MeV/c^2} \equiv (1777.0 \pm 0.3)\mathrm{MeV/c^2}$.

Gauge Bosons ($J^P = 1^-$)						
Force	Gauge Boson	Charge (e)	Mass (GeV/c^2)	Full Width (GeV)	Decay Mode	Branching Ratio (%)
E-M	γ	$< 5 \times 10^{-30}$	$< 2 \times 10^{-16}\,eV/c^2$	stable		
Weak (Charged)	$W^\pm$	±1	80.41($\pm$10)	2.06($\pm$6)	$e\nu_e$	10.9($\pm$4)
					$\mu\nu_\mu$	10.2($\pm$5)
					$\tau\nu_\tau$	11.3($\pm$8)
					hadrons	67.8($\pm$10)
Weak (Neutral)	Z^0	0	91.187($\pm$7)	2.490($\pm$7)	ee	3.366($\pm$8)
					$\mu\mu$	3.367($\pm$13)
					$\tau\tau$	3.360($\pm$15)
					$\nu\nu$	20.01($\pm$16)
					hadrons	69.90($\pm$15)
Strong	g	0	0	stable		

Pseudoscalar Mesons ($J^P = 0^-$)

Particle	Quark Content	Mass (MeV/c^2)	Mean Life (s) or Width (keV)	Decay Mode	Branching Ratio (%)
$\pi^\pm$	$u\bar{d}, d\bar{u}$	139.5700(±4)	$2.6033(\pm5) \times 10^{-8}$	$\mu^-\bar{\nu}_\mu$	≈ 100
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	134.9764(±6)	$8.4(\pm6) \times 10^{-17}$	$\gamma\gamma$	98.80(±3)
η	see note a	547.3(±1)	1.2(±1)	$\gamma\gamma$	39.2(±3)
				$\pi^0\pi^0\pi^0$	32.2(±4)
				$\pi^+\pi^-\pi^0$	23.1(±5)
				$\pi^+\pi^-\gamma$	4.8(±1)
η'	see note a	957.8(±1)	0.20(±2)	$\pi^+\pi^-\eta$	44(±2)
				$\rho^0\gamma$	30(±1)
				$\pi^0\pi^0\eta$	21(±1)
$K^\pm$	$u\bar{s}, s\bar{u}$	493.677(±16)	$1.239(\pm2) \times 10^{-8}$	$\mu^-\bar{\nu}_\mu$	63.5(±2)
				$\pi^-\pi^0$	21.2(±1)
				$\pi^+\pi^-\pi^-$	5.59(±5)
				$\pi^0\mu^-\bar{\nu}_\mu$	3.18(±8)
				$\pi^0 e^-\bar{\nu}_e$	4.82(±6)
$K^0, \overline{K^0}$	$d\bar{s}, s\bar{d}$	497.67(±3)	K^0_S $0.8934(\pm8) \times 10^{-10}$	$\pi^+\pi^-$	68.6(±3)
				$\pi^0\pi^0$	31.4(±3)
			K^0_L $5.17(\pm4) \times 10^{-8}$	$\pi^0\pi^0\pi^0$	21.1(±3)
				$\pi^+\pi^-\pi^0$	12.6(±2)
				$\pi^\pm\mu^\mp\nu_\mu$	27.2(±3)
				$\pi^\pm e^\mp\nu_e$	38.8(±3)
$D^\pm$	$c\bar{d}, d\bar{c}$	1869.3(±5)	$1.06(\pm2) \times 10^{-12}$	$e^- + \text{any}^b$	17(±2)
				$K^- + \text{any}$	24(±3)
				$K^+ + \text{any}$	6(±1)
				$K^0 + \text{any}$	
				plus	
				$\overline{K^0} + \text{any}$	59(±7)
$D^0, \overline{D^0}$	$u\bar{c}, c\bar{u}$	1864.6(±5)	$0.415(\pm4) \times 10^{-12}$	$K^- + \text{any}^c$	53(±4)
				$K^+ + \text{any}$	3.4(±5)
				$e^+ + \text{any}$	6.8(±3)
				$\mu^+ + \text{any}$	6.6(±8)
				$\overline{K^0} + \text{any}$	
				plus	
				$K^0 + \text{any}$	42(±5)
$D_s^\pm$	$c\bar{s}, s\bar{c}$	1968.5(±6)	$0.47(\pm2) \times 10^{-12}$	seen	
$B^\pm$	$u\bar{b}, b\bar{u}$	5279(±2)	$1.65(\pm4) \times 10^{-12}$	seen	
$B^0, \overline{B^0}$	$d\bar{b}, b\bar{d}$	5279(±2)	$1.56(\pm4) \times 10^{-12}$	seen	
$B_s^0, \overline{B_s^0}$	$s\bar{b}, b\bar{s}$	5369(±2)	$1.54(\pm7) \times 10^{-12}$	seen	
η_c	$c\bar{c}$	2980(±2)	13(±4) MeV	hadrons	

[a] η and η' are linear combinations of the quark state $(u\bar{u} + d\bar{d})/\sqrt{2}$ and $s\bar{s}$.
[b] D^- decay modes; [c] D^0 decay modes.

Vector Mesons ($J^P = 1^-$)					
Particle	Quark Content	Mass (MeV/c^2)	Full Width (MeV)	Decay Mode	Branching Ratio (%)
$\rho^\pm$	$u\bar{d}, d\bar{u}$	770.0(±8)	151(±1)	$\pi\pi$	100
ρ^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$				
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	781.9(±1)	8.41(±9)	$\pi^+\pi^-\pi^0$	88.8(±7)
				$\pi^0\gamma$	8.5(±5)
				$\pi^+\pi^-$	2.2(±3)
ϕ	$s\bar{s}$	1019.413(±8)	4.43(±5)	K^+K^-	49.1(±8)
				$K^0_L K^0_S$	34.1(±6)
$K^{*\pm}$	$u\bar{s}, s\bar{u}$	891.7(±3)	50.8(±9)	$K\pi$	≈ 100
$K^{*0}, \overline{K^{*0}}$	$d\bar{s}, s\bar{d}$	896.1(±3)	50.5(±6)	$K\pi$	≈ 100
$D^{*\pm}$	$c\bar{d}, d\bar{c}$	2010.0(±5)	< 0.13	$D^0\pi^{-a}$	68(±1)
				$D^-\pi^0$	31(±3)
$D^{*0}, \overline{D^{*0}}$	$u\bar{c}, c\bar{u}$	2006.7(±5)	< 2.1	$D^0\pi^{0b}$	62(±3)
				$D^0\gamma$	38(±3)
$D_s^{*\pm}$	$c\bar{s}, s\bar{c}$	2112.4(±7)	< 1.9	seen	
B^*	$u\bar{b}, b\bar{u}, d\bar{b}, b\bar{d}, s\bar{b}, b\bar{s}$	5325(±2)		$B\gamma$ seen	
J/ψ	$c\bar{c}$	3096.88(±4)	87(±5) keV	hadrons	87.7(±5)
				e^+e^-	6.0(±2)
				$\mu^+\mu^-$	6.0(±2)
$\Upsilon(1s)$	$b\bar{b}$	9460.4(±2)	53(±2) keV	$\tau^+\tau^-$	2.7(±2)
				e^+e^-	2.5(±2)
				$\mu^+\mu^-$	2.48(±7)

[a] D^{*-} decay modes; [b] D^{*0} decay modes.

Baryons ($J^P = 1/2^+$)					
Particle	Quark Content	Mass (MeV/c^2)	Mean Life (s) or Full Width (MeV)	Decay Mode	Branching Ratio (%)
p	uud	938.2723(±3)	$> 1.6 \times 10^{25}$ years		
n	udd	939.5656(±3)	887(±2)	$pe^-\bar{\nu}_e$	100
Λ^0	uds	1115.683(±6)	$2.63(\pm 2) \times 10^{-10}$	$p\pi^-$	63.9(±5)
				$n\pi^0$	35.8(±5)
Σ^+	uus	1189.37(±7)	$0.799(\pm 4) \times 10^{-10}$	$p\pi^0$	51.6(±3)
				$n\pi^+$	48.3(±3)
Σ^0	uds	1192.64(±2)	$7.4(\pm 7) \times 10^{-20}$	$\Lambda^0\gamma$	100
Σ^-	dds	1197.45(±3)	$1.48(\pm 1) \times 10^{-10}$	$n\pi^-$	99.848(±5)
Ξ^0	uss	1314.9(±6)	$2.90(\pm 9) \times 10^{-10}$	$\Lambda^0\pi^0$	99.54(±5)
Ξ^-	dss	1321.3(±1)	$1.64(\pm 2) \times 10^{-10}$	$\Lambda^0\pi^-$	99.89(±4)
Λ_c^+	udc	2284.9(±6)	$2.1(\pm 1) \times 10^{-13}$	seen	
Λ_b	udb	5624(±9)	$1.14(\pm 8) \times 10^{-12}$	seen	
Baryons ($J^P = 3/2^+$)					
Δ	uuu, uud udd, ddd	≈ 1232	≈ 120	$N\pi$	> 99
Σ^*	uus, uds, dds	≈ 1385	≈ 36	$\Lambda^0\pi$	88(±2)
				$\Sigma\pi$	12(±2)
Ξ^*	uss, dss	≈ 1530	≈ 9	$\Xi\pi$	100
Ω^-	sss	1672.5(±3)	$0.82(\pm 1) \times 10^{-10}$	$\Lambda^0 K^-$	67.8(±7)
				$\Xi^0\pi^-$	23.6(±7)
				$\Xi^-\pi^0$	8.6(±4)

MATTER

Leptons

- Spin $\frac{1}{2}$
  - charged
  - neutral
  - neutrinos (massless?)

Hadrons (consist of quarks)

- Baryons (3 quarks) (+anti....) $\frac{1}{2}$ integer spin
- Mesons (quark + antiquark pair) integer spin