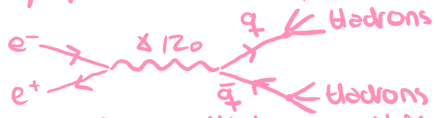
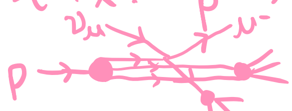
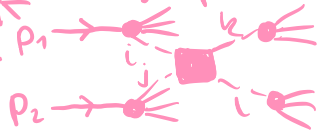
PARTICLE

1.

* Jets are collimated streams of hadrons that are produced in high-energy particle collisions
* They reflect the fact that partons (quarks and gluons) cannot be observed directly due to the fundamental property of (color) confinement
* When quarks and gluons are produced in collisions they travel away from each other
* The running coupling constant α_s increases as the distance/mom. transfer/ CM? energy increases/decreases/decreases, and as a result the strength of the strong interaction grows as the partons move away from each other, until they eventually hadronize to produce the jets of hadrons
* Lepton-lepton collisions: 
* High energy electron-positron pairs collide, annihilate, produce quark-antiquark pair, followed by fragmentation converting the pair to two jets of hadrons.
* Complicated process. However, jet direction defined by sum over all momenta of particles in the jet reflects the directions of the parent quark/antiquark
* This is because QCD inter. weak at short distances (asymptotic freedom) hence the quark-antiquark pair do not interact strongly until they are separated by a distance of ≥ 1fm.
* Small momentum transfer at these distances, hence the jets develop almost exactly in the original quark-antiquark directions
* Thus, the jet angular dist. reflects ang. dist of the quark and antiquark in the basic reaction $e^+ + e^- \to q + \bar{q}$.
* In addition to back-to-back jets, sometimes high energy gluons emitted from $q/\bar{q}$ before fragmentation (like bremsstrahlung), eventually fragment. → three jet event.
* Deep inelastic scattering like $l^- + p \to l^- + X$: 
* Deep inelastic neutrino scattering:  $\nu_\mu + p \to \mu^- + X$
* Di-jet production in proton-proton collision:  i,j,k,l = partons

2.

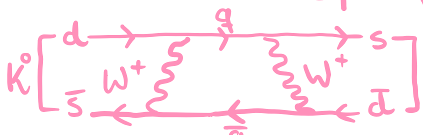
* Neutral spin-0 scalar boson, couples to all particles w/ mass (including self)
* Gauge invariance would imply that $W^\pm$ and Z^0 have zero mass
* Higgs field nonzero inn vacuum and not invariant under gauge transf.
* Nonzero expectation value in the vacuum state, contrary to EM and color fields
* Gauge bosons do not have to be massless when field is not invariant, and this is a form of spontaneous symmetry breaking
* Couples to fermions with strength $g_{Hff} = \sqrt{2}\, g_W (m_f / m_W)$ as

 ⇐ can be tested by measuring g_{Hff} and comparing to known fermion masses

* Experimental consequences of the fact that the coupling strength is proportional to the fermion masses are that the dominant fermionic decay modes are to the heaviest fermions such as b and τ (not t), which in turn decay to lighter particles
* Much more stable than $W^\pm$ and Z^0 because its couplings to relatively light particles are heavily suppressed. This is obvious since $\Gamma(H \to f\bar{f}) = N \alpha_W \left(\frac{m_f^2}{m_W^2}\right) m_H c^2$, $\alpha_W = \frac{g_W^2}{4\pi} = 0.0042$. N = 1 for leptons and N = 3 for quarks (three color states)
* Higher order diagrams have decay widths comparable to the first order diagrams. Higher order diag like 

3

* Two neutral kaon states: $K^0(498) = d\bar{s}$ and $\bar{K}^0(498) = s\bar{d}$, w/ $S=1$ and $S=-1$
* Strangeness not conserved in weak interactions: The states can be converted to each other by higher order weak processes such as



$q = u, c, t$ and $\bar{q} = \bar{u}, \bar{c}, \bar{t}$

* Normally forbidden for other particle-antiparticle pairs: n and $\bar{n}$ have opposite B, π^+ and π^- have opposite Q.
* For an initial beam of K^0 the identity of the decaying particle as either K^0 ($S=1$) or $\bar{K}^0$ ($S=-1$) will not necessarily be the same as that of the kaon produced initially (K^0) due to the strangeness oscillations (see higher order weak interaction diagram ↑).
* The identity of the decaying particle, and thus its strangeness, can be identified by detecting it via the allowed leptonic decays (e^+ for K^0 and e^- for $\bar{K}^0$).
* Neutral kaon K^0 w/ $S=1$ produced in strong interaction $\pi^- + p \to K^0 + \Lambda^0$
* Produced particle travels through space and the measured strangeness S oscillates in time between $S=1$ and $S=-1$, similar to flavour oscillations of neutrinos
* Ignoring the very small CP violations (Q. 11) the initially produced state is $|K^0, \vec{0}\rangle = 1/\sqrt{2}(|K^0_S, \vec{0}\rangle + |K^0_L, \vec{0}\rangle)$, while after some time t it will be $1/\sqrt{2}(a_S(t)|K^0_S, \vec{0}\rangle + a_L(t) ..)$
* Intensitities $I(K^0 \to K^0)$ and $I(K^0 \to \bar{K}^0)$ for initial K^0 beam evolve like

t/τ_S ($\tau_S = K^0_S$ lifetime)

* Furthermore, K^0 decays into e^+ while $\bar{K}^0$ decays into e^-, hence $N(e^+) \gg N(e^-)$ in the beginning. However, as $I(K^0 \to \bar{K}^0)$ increases while $I(K^0 \to K^0)$ decreases, the no. of decays to e^- increases as well. As a result, we have that the ratio $(N^+ - N^-)/(N^+ + N^-)$ evolves like

proper time

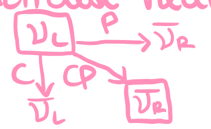
(N^+ slightly larger than N^- towards the end due to CP viol. ???)

4.

* Helicity states of a spin-1/2 particle:

right-handed left-handed

Spin quantized along the direction of motion of the particle — positive helicity is right-handed state and $+\hbar/2$ spin along axis.
* Spin direction corresponds to rot. motion in right/left-handed sense when viewed along momentum direction.
* Only left-handed neutrinos ν_L and right-handed antineutrinos $\bar{\nu}_R$ are observed in nature



Violates C-invariance, which would require ν and $\bar{\nu}$ to have identical weak interactions. Also violates P-invariance, which would require ν_L and ν_R to have identical weak interactions since the parity operator reverses the mom. while leaving spin unchanged.

* Compatible w/ CP invariance: converts left-handed neutrino to r-hand $\bar{\nu}$
* In fact, the weak interaction violates parity invariance because it distinguishes between all right-handed and left-handed particles.
* In the Wu experiment where Wu and her colleagues studied the beta-decay of cobalt-60 a neutron in the nucleus decays into a proton, emitting an electron: $n \to p + e^- + \bar{\nu}_e$
* The ^{60}Co nuclei polarized using a strong magnetic field at very low temperatures
* The direction of emitted electrons was measured relative to the polariz. axis
* Parity invariance would require the electrons to be emitted symmetrically w/ respect to the polarization direction. However, the experiment observed that electrons were preferentially emitted in the direction opposite to the nuclear spin
* Reflects the V-A (vector minus axial) nature of the weak interaction.
* Emitted anti-neutrino is right-handed and thus emitted in a direction that maximizes the helicity configuration required by the weak interaction.

5.

* The coupling constant α_s in QCD acts in many ways like the fine structure constant α_{EM} in QED, and characterizes the strength of the strong interaction.
* Running coupling constant refers to the fact that α_s depends on the Lorentz invariant quantity $\mu^2 \equiv |\vec{q}^{\,2}c^2 - E_q^2|$, where $\vec{q}$ and E_q are the transferred momentum and energy between the interacting quarks/gluons.
* Decreases with μ, i.e. it is smaller for short distances where the momentum transfer $\vec{q}$ increases, a property very different from EM force - asymptotic freedom
* Increases with distance - color confinement.
* J/ψ ground state of charmonium ($c\bar{c}$), Υ G.S. of bottomonium ($b\bar{b}$)
* Below charmed threshold: Decay slowly to noncharmed hadrons by mechanisms involving the annihilation of a charmed quark-antiquark pair:

* Above threshold: Decay quickly (broad peaks in R vs. E_{cm} plot) to charmed states

Like 

$q = u, d, s$ correct diagram?

* OZI rule: creation/annihilation of $c\bar{c}$ or $b\bar{b}$ pairs heavily suppressed relative to $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ - results in narrow peaks below charm/bottom thresholds and broader peaks above.
* Stronger strong interaction - longer distances - lower energies - creation/annihilation of $c\bar{c}$ and $b\bar{b}$ suppressed - below threshold.
* Weaker strong interaction - shorter distances - higher energies - decays above thresholds occur with large widths

6.

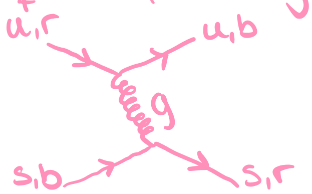
* The Standard Model of particle physics is a theory describing three of the four known fundamental forces (not gravity) and classifying all known elementary particles. It includes the electromagnetic, strong and weak forces which are mediated by gauge bosons.
* EM force is mediated by the massless and electrically neutral photon. Affects all particles with charge Q and is described in detail by QED.
* Weak force is mediated by the massive $W^\pm$ (charges $Q = \pm 1$) and Z^0 bosons (Z^0 has $Q=0$) and affects all fermions. It is responsible for beta decay and is described in detail with electroweak theory as being unified w/ EM.
* Weak force has characteristic strength larger than gravity and smaller than EM and strong force (hence name), and has very short range due to the mediator bosons being massive (Yukawa)
* Strong force has largest characteristic strength, is mediated by massless gluons (infinite range) and affects both quarks and gluons (not leptons).
* Responsible for binding quarks together in hadrons, and is described in detail w/ QCD.
* Particles of standard model categorized into fermions (half-integer) and bosons.
* Fermions are matter particles and are divided into quarks and leptons, all of which have their corresponding antiparticles.
* Draw diagram! Divided into three generations.
* Quarks - Flavors: Up (u), down (d), charm (c), strange (s), top (t), bottom (b)
* Carry color charge and participate in all four forces. Up-type quarks have $Q = +2/3$ and down-types have $Q = -1/3$. Mention generations.
* Leptons: Types are electron (e), muon (μ) and tau (τ) and their neutrinos.
* Do not carry color charges. e, μ and τ have $Q = -1$ and thus interact w/ EM and weak - neutrinos are neutral and only interact weakly.
* Mention generations
* Gauge bosons have spin-1 and are force carriers, mediating the interactions

between fermions. Photon for EM, $W^{\pm}$ and Z^0 for weak, gluon g for strong
* Higgs boson H is a scalar boson w/ spin-0. Gives mass to the other particles (including self) through Higgs mechanism. The particles interact w/ the Higgs field.

7.
* Quantum numbers describe properties of particles and are conserved and violated in different interactions.
* Electric charge Q: Conserved in all interactions
* Total lepton number L, which is the sum of the individual lepton numbers L_e, L_μ, L_τ. Total lepton number is always conserved, and the individual nr. are pos/neg for particle/anti-particle. Individual lepton numbers can be violated in weak interaction - neutrino oscillations
* Total baryon number B, defined as $\pm\frac{1}{3}$ for quarks/antiquarks, making it ± 1 for baryons/antibaryons and 0 for mesons. Conserved in all interactions
* Strangeness S, charm C, bottomness $\tilde{B}$ and topness T: Quantum numbers associated w/ the presence of strange, charm, bottom and top quark
* $S=-1/+1$ for $s/\bar{s}$ and $\tilde{B}=-1/+1$ for $b/\bar{b}$ while $C=+1/-1$ for $c/\bar{c}$ and $T=+1/-1$ for $t/\bar{t}$.
* Conserved in strong and EM but can be violated in weak.
* Isospin I and its third component I_3: Quantum numbers related to the symmetry of the strong interaction, analogous to spin but for the internal symmetry of quarks. Conserved only for all strong interactions.
* Isospin symmetry refers to symmetry of u and d quarks
* $I_3=+\frac{1}{2}$ for u and $I_3=-\frac{1}{2}$ for d, 0 for all others. $I_3=\frac{1}{2}(n_u-n_d)$ for any hadron. $\bar{d}$ has $I_3=\frac{1}{2}$ and $I_3=-\frac{1}{2}$ for $\bar{u}$. I adds like ang. mom.
* Hypercharge $Y=B+S+C+\tilde{B}+T$ conserved in strong only?
* Mention color charge, color isospin and color hypercharge! Must be zero for all particles before and after all reactions due to color confinem.
* Parity describes the symmetry of a particle's wave function under spatial inversion. Either +1 or -1. Only violated in weak interactions
* Charge conjugation (C-parity describes the symmetry of a particle when it is switched w/ its antiparticle (hence inverting Q, L, B, S, C, $\tilde{B}$, T). Only violated in weak interaction. Eigenstates of C-parity are their own antiparticles and have eigvals ± 1.

8.
* QCD is the theory describing the strong interaction. Governs the behavior of quarks and gluons, which are the fundamental constituents of hadrons.
* Quarks are elementary particles (fermions) that come in six flavors divided in three generations: Gen 1 are lightest - up (u) and down (d) - make up stable hadrons (protons uud and neutrons udd). Gen 2 are heavier - charm (c) and strange (s). Gen 3 are heaviest - top (t) and bottom (b).
* All quarks have antiparticles w/ opposite Q.
* Up-type quarks u, c and t have charge $Q=+\frac{2}{3}$, down-type quarks d, s, b have charge $Q=-\frac{1}{3}$
* Gluons are massless gauge bosons that mediate the strong force - infinite range of force since they are massless (Yukawa)
* Quarks posess a property known as color charge: $r=+\frac{1}{3}$, $g=+\frac{1}{3}$, $b=-\frac{2}{3}$ => bound states of quarks always have total color charge 0 (color confinement). Obvious since anti-quarks have color charge either $\bar{r}=-\frac{1}{3}$, $\bar{g}=-\frac{1}{3}$ or $\bar{b}=+\frac{2}{3}$, and mesons (quark-antiquark) thus have either $r\bar{r}$, $g\bar{g}$ or $b\bar{b}$ comb. Baryons (anti-baryons) are qqq ($\bar{q}\bar{q}\bar{q}$) and must therefore have rgb ($\bar{r}\bar{g}\bar{b}$).
* Gluons can exist in 8 color states - interact w/ strong int. unlike photons in EM. Thus cannot be observed alone (like quarks) due to color confinement
* The gluon color states are combinations of color and anti-color
* As quarks try to separate and "break free" from each other the strong force becomes stronger, leading to the creation of $q\bar{q}$ pairs when enough energy is provided - confinement.

* Gluons mediate force between quarks and thus confined within hedrons as well.
* Strong interaction strength characterized by the strong coupling constant α_s
* At distances $r \leq 0.1\,fm$ pot. behaves like a Coulomb pot. $\Rightarrow V(r) = -\frac{4}{3}\hbar c \alpha_s / r \Rightarrow$ dom. by one-gluon exchange and we can use perturbative methods like in QED. α_s decreases with decreasing r but this effect is negligible for distances below 0.1fm
* Asymptotic freedom ↗ quarks and gluons behave almost like free particles
* Potential increases approx. linearly with distance for distances $r \gtrsim 1fm$, ie $V(r) \approx \lambda r$. In that case the potential is so large that we cannot use perturb. methods. As the distance between quarks/gluons increases they split to form hadrons always? because potential increases?
* At extremely high temp and densities (early universe, heavy ion collisions), quarks and gluons can exist in a deconfined state known as the quark-gluon plasma (QGP).
* Quarks and gluons no longer confined within hadrons but move freely over larger volumes
* QGP exhibits properties such as very low viscosity and strong collective behavior, indicating strong interactions among constituents
* Studied at the quark-gluon plasma laboratory (LQGP) – has been involved in PHENIX exp. at RHIC, BNL and is currently involved in the ALICE exp. at the LHC, CERN. Heavy ion collisions of ultrarelativistic particles.
* RHIC – Relativistic Heavy Ion Collider, BNL – Brookhaven National Laboratory
* Simple Feynman diagram showing exchange of gluon between two quarks, changing their color charges



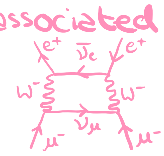
color is changed, not flavor!
flavor change (like β decay) is weak interaction

9.

* Electroweak unification is a theoretical framework that unifies the EM and weak interactions into a single electroweak force. – At large energies the ratio between Z^0 and γ cross sections is ~ 1
* Based on the gauge group $SU(2)_L \times U(1)_Y$, where $SU(2)_L$ corresponds to weak isospin symmetry and $U(1)_Y$ to weak hypercharge symmetry.
* The theory predicts four gauge bosons: W^1, W^2, W^3 (associated w/ $SU(2)_L$) and B (associated w/ $U(1)_Y$) which mix to form the physical gauge bosons W^+, W^-, Z^0 and γ.
* The Higgs mechanism is responsible for spontaneous breaking of the electroweak symmetry – the vacuum expect. value of the Higgs field breaks $SU(2)_L \times U(1)_Y$ down to EM $U(1)_{em}$ symmetry.
* This process gives $W^\pm$ and Z^0 mass while leaving γ massless.
* The charged bosons are given by $W^\pm = \frac{1}{\sqrt{2}}(W^1 \pm i W^2)$
* Mixing of W^3 and B leads to γ and Z^0:

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\vartheta_W & \sin\vartheta_W \\ -\sin\vartheta_W & \cos\vartheta_W \end{pmatrix} \begin{pmatrix} B \\ W^3 \end{pmatrix}$$, ϑ_W is the weak mixing angle defined as $\cos\vartheta_W = \frac{M_W}{M_Z}$

* Electroweak theory was proposed mainly to solve problems associated with Feynman diagrams in which more than one W boson was exchanged, such as



$e^+\mu^- \to e^+\mu^-$

* Such higher order contributions are expected and observed experimentally to be small.
* However, when they are explicitly calculated in non-unified theory they are found to be proportional to divergent integrals, meaning that they are infinite.
* Problem is solved when diagrams involving the exchange of Z^0 and γ are taken into account as well. These contributions are also divergent by themselves, but together all infinities cancel, such that the contributions become well-defined and finite.

10.

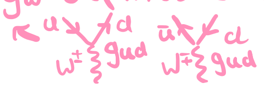
* Quark mixing refers to the phenomenon where quarks of different flavors can transform

into each other via weak interactions.

* Described mathematically with the CKM matrix, which encapsulates the probabilities of different quark transitions.
* The down-type quark eigenstates d, s and b of the strong interaction are not eigenstates of the weak interaction, hence the mixing.
* The eigenstates of the weak interaction are given in terms of the CKM matrix as

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \approx \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Rightarrow \begin{matrix} d' \approx \cos\theta_c d + \sin\theta_c s \\ s' \approx \cos\theta_c s - \sin\theta_c d \\ b' \approx b \end{matrix}$$

* Observed experimentally that neglecting the mixing of b with d and s is a good first approx.
* $\theta_c \approx 13^\circ$ is the Cabibbo angle
* Lepton-quark symmetry is applied to the doublets $\binom{u}{d'}$ and $\binom{c}{s'}$, meaning that these two quark generations are expected to have weak interactions identical to the first two lepton generations $\binom{\nu_e}{e^-}$ and $\binom{\nu_\mu}{\mu^-}$ → obtains basic $W^\pm$-quark vertices by replacing $\nu_e \to u$, $e^- \to d$, $\nu_\mu \to c$, $\mu^- \to s$.
* As a result we have that the coupling constants $g_{ud} = g_{cs} = g_W \cos\theta_c$, g_W defines strength of leptonic weak interactions, Cabibbo angle accounts for quark mixing. We thus have $g_{us} = -g_{cd} = g_W \sin\theta_c$, hence u decaying to s is Cabibbo-suppressed since $\cos\theta_c > \sin\theta_c$, but still possible. The $ud'W$ vertex can be expressed as



$d' = \cos\theta_c d + \sin\theta_c s$ $\quad g_{ud} = g_W \cos\theta_c$ $\quad g_{us} = g_W \sin\theta_c$ $\quad = \tan^2\theta_c \approx 1/20$

Cabibbo-allowed Cabibbo-suppressed

* Cabibbo-suppressed because rates are typically reduced by a factor of $g_{us}^2/g_{ud}^2 = g_{cd}^2/g_{cs}^2$
* Example of quark mixing: Lambda decay $\Lambda \to \pi^- + p$

11.

* CP violation refers to the phenomenon where the combined symmetry of charge conjugation (C-parity) and parity is not conserved in certain weak interactions. Crucial for understanding matter-antimatter asymmetry. Complex phases in CKM-mat.
* No way to distinguish K^0 and $\bar{K}^0$ in weak interactions using quantum numbers when observed particles correspond to linear comb. of them. (see Q. 3)
* We have that $\hat{C}|K^0, \vec{p}\rangle = -|\bar{K}^0, \vec{p}\rangle$ and $\hat{C}|\bar{K}^0, \vec{p}\rangle = -|K^0, \vec{p}\rangle$ by standard phase conv.
* Kaons have negative intrinsic parity since d and s have pos while $\bar{d}$ and $\bar{s}$ have negative, hence $\hat{P}|K^0, \vec{0}\rangle = -|K^0, \vec{0}\rangle$ and same for $|\bar{K}^0, \vec{0}\rangle$.
* Combining we have $\hat{C}\hat{P}|K^0, \vec{0}\rangle = |\bar{K}^0, \vec{0}\rangle$ and $\hat{C}\hat{P}|\bar{K}^0, \vec{0}\rangle = |K^0, \vec{0}\rangle$.
* Eigenstates of $\hat{C}\hat{P}$: $K^0_{1,2} = \frac{1}{\sqrt{2}}(|K^0, \vec{0}\rangle \pm |\bar{K}^0, \vec{0}\rangle)$, $CP = \pm 1$
* CP conservation: K^0_1 decays entirely to states w/ $CP = +1$ and K^0_2 entirely to states w/ $CP = -1$.
* Decay to $\pi^0\pi^0$ would require relative orbital ang. mom. $L = 0$ since spin of kaon is 0. Since intrinsic parity of π^0 is negative we thus have $P = P_{\pi^0}^2(-1)^L = 1$. C-parity of π^0 is +1 since it is its own antiparticle, hence $C = (C_{\pi^0})^2 = 1$. We thus have $CP = 1$ for $\pi^0\pi^0$ final state (same for $\pi^\pm\pi^\mp$)
* For $\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ final states we have two orbital angular momenta: $\vec{L}_{12}$ for one pair ($\pi^+\pi^-$ or $\pi^0\pi^0$) in their CM frame, and the $\vec{L}_3$ of the third pion about the CM of the first two in the total CM frame. We must have $\vec{L} = \vec{L}_{12} + \vec{L}_3 = \vec{0} \Rightarrow L_{12} = L_3 \Rightarrow P = (P_\pi)^3(-1)^{L_{12}}(-1)^{L_3} = (-1)^3(-1)^{2L_{12}}$ while $C = (C_{\pi^0})^3 = 1$ so $CP = -1$ for $\pi^0\pi^0\pi^0$ (same for $\pi^+\pi^-\pi^0$).
* From experiment: K^0_S and K^0_L. Almost equal masses but very different lifetimes and decay modes: K^0_S (almost) only to 2 pions ($CP = +1$) while K^0_L mostly to three ($CP = -1$).
* Assume from $CP(K^0_1) = +1$ and $CP(K^0_2) = -1$ that $K^0_S = K^0_1$ and $K^0_L = K^0_2$.
* Although small branching ratio, $K^0_L \to \pi^+ + \pi^-$ also observed ⇒ CP violation.
* CP violation also observed in $K^0 \to \pi^- + e^+ + \nu_e$ and $\bar{K}^0 \to \pi^+ + e^- + \bar{\nu}_e$ as well later.
* Starting with a beam of K^0 with CP invariance would imply $K^0_S = K^0_1$ and $K^0_L = K^0_2$, and thus equal amounts of K^0_S and K^0_L. Since K^0_S decays much faster than K^0_L we

should eventually have mostly K_L^0, which we expect to have equally large K^0 and $\bar{K}^0$ components. These participate in semi-leptonic decays resulting in e^+ and e^- respectively, hence we expect to observe $N(e^+) = N(e^-)$ from the two decays.

* $K_L^0 \neq K_2^0$ (not eigenstate of CP) => asymmetry in $N(e^+)$ and $N(e^-)$ => observed.
* $|K_S^0, \vec{0}\rangle = (1+|\varepsilon|^2)^{-1/2}(|K_1^0, \vec{0}\rangle + \varepsilon|K_2^0, \vec{0}\rangle)$, $|K_L^0, \vec{0}\rangle = (1+|\varepsilon|^2)^{-1/2}(\varepsilon|K_1^0, \vec{0}\rangle + |K_2^0, \vec{0}\rangle)$, ε is small and complex.
* Asymmetry $A \equiv (N^+ - N^-)/(N^+ + N^-) = 2\mathrm{Re}(\varepsilon)$ for a pure K_L^0 beam (neglect terms of order $\geq |\varepsilon|^2$)
* CP-violation by mixing: CP-forbidden K_1^0 component in the K_L^0 decays via the CP-allowed processes $K_1^0 \to \pi^+\pi^-$ and $K_1^0 \to \pi^0\pi^0$??? **why is this violation? because K_L^0 should be only K_2^0?**
* Direct CP-violation: K_2^0 component in the K_L^0 decays directly to pion pairs via the CP-violating reactions $K_2^0 \to \pi^0\pi^0$ and $K_2^0 \to \pi^+\pi^-$
* Calculation of ε shows that CP-viol by mixing is dominant mechanism for CP violation in K_L^0 decays

Weak neutral current reactions

* For example $\nu_\mu + N \to \nu_\mu + X$, N is a nucleon and X is a set of hadrons allowed by conservation laws

All weak interactions involving exchange of Z^0 boson

Weak charged current reactions

* Simplest type is purely leptonic processes such as muon decay $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$, but also include purely hadronic processes like Lambda decay $\Lambda \to p + \pi^-$ and semi-leptonic reactions such as neutron decay (β^-) $n \to p + e^- + \bar{\nu}_e$

Neutrino oscillations

* Neutrinos originally thought to be massless, but not possible due to neutrino oscillations
* Beam of neutrinos of one type, say ν_μ, develops components of other types (ν_e and/or ν_τ) as it travels over long distances
* We must have neutrino mixing: Assumption that the neutrino states ν_e, ν_μ and ν_τ that couple to e^-, μ^- and τ^-, respectively, do not have definite masses, but instead are linear combinations of the mass eigenstates ν_1, ν_2 and ν_3 w/ masses m_1, m_2, m_3, respectively.
* Neutrino oscillations can then occur if m_1, m_2, m_3 (eigenvalues) are all different, i.e. they cannot all be zero and hence the neutrinos must have mass
* Focusing on only neutrino types ν_α and ν_β we can write an initial state as $|\nu_\alpha, \vec{p}\rangle = |\nu_i, \vec{p}\rangle\cos\theta_{ij} + |\nu_j, \vec{p}\rangle\sin\theta_{ij}$, where θ_{ij} is the mixing angle determined from experiment and i, j are indices referring to two of the mass eigenstates ν_1, ν_2 and ν_3.

α-particles energy above 26 MeV Rutherford formula does not hold - scattering intensity vs. α-particle energy

NUCLEAR

1.

* The strong nuclear force is responsible for holding nucleons in atomic nuclei together, and it is a manifestation of the strongest of the four fundamental forces. It has a very short range though, of approximately 1-2 fm, which reflects the fact that the force mediators are the massive pions (π^+, π^- and π^0 mesons).
* Strongly repulsive at distances below ~ 0.7 fm, which ensures that the nucleons do not collapse in on themselves
* At distances where the force is attractive the nucleon-nucleon interaction can be described using the Yukawa potential $V(r) = -g^2 e^{-\alpha m r}/r$, where g and α scaling constants and m is the mass of the force mediator particle, which is also used when modelling the fundamental strong interaction, EM and weak interactions. We see that the potential falls significantly much faster with distance the larger the mass m, hence why the nuclear force has such a short effective range (while the EM interaction is infinite, γ is massless).
* The short range has been observed in α-scattering experiments such as in Rutherford scattering. Only Coloumb interaction when α-particle does not have sufficient energy.
* When high enough energy – α penetrates C-barrier – nucleus acts as an absorbing sphere
* To stabilize nuclei we must have a balance between the strong nuclear force and the Coloumb repulsion between the constituents protons.
* If balance is not maintained the nuclei can become unstable, leading to phenomena like radioactive decay or nuclear fission.
* The strong nuclear force plays an essential role in storing energy that is harnessed in nuclear power plants and nuclear weapons. Energy in the form of work is required to bring charged protons together against their electric repulsion.
* This energy is stored in the form of negative binding energy when the protons and neutrons are bound together by the nuclear force to form the nucleus.
* As a result the energy of the nucleus is less than the sum of the energies of the constituent nucleons – its mass is smaller than the sum of their masses.
* The binding energy per nucleon is largest for iron and decreases on either side of this graph, hence large amounts of energy are released as lighter elements fuse to heavier elements, and when heavier elements undergo fission (split up into lighter, more stable nuclei)
* The nuclear force is also charge independent, meaning that it is equally strong for protons as for neutrons. As a result, nuclei with large proton number can thus increase the number of neutrons to stay stable, since it increases the attractive potential caused by the nuclear force without increasing the Coloumb repulsion.

excited states have similar spin, parity and ΔE ↓

* Part of this is charge-symmetry (equality of p-p and n-n forces if they are in the same spin state) – observed experimentally in mirror nuclei (same A, $Z \Leftrightarrow N$)
* The potential experienced by nucleons in the nucleus must reflect the combination of the strong nuclear force and the repulsive EM force between the protons, and a commonly used model is the Woods-Saxon potential: $V(r) = -V_0/(1+e^{(r-R)/a})$, where $V_0 \approx 50$ MeV determines the potential well depth and a, normally set to around 0.5 fm, is a parameter which controls how rapidly the potential goes to zero (faster for smaller a).
* $R = r_0 A^{1/3}$ corresponds to the effective nuclear radius. $r_0 = 1.25$ fm and A is the mass number. We see that the potential well widt increases with R and thus w/ A – the number of nucleons.
* Woods-Saxon shape:

Woods-Saxon combined with repulsive barrier and Coloumb potential:

* Also called the residual strong force, because it is a residual effect of the more fundamental strong interaction that binds quarks to form the nucleons that make up nuclei. On the quark scale the force is mediated by massless gluons and thus has infinite range
* On the large scale the strong nuclear force acts like its own fundamental force with pions as force carriers, although in reality it is the fundamental strong interaction mediated by gluons acting multiple times in a row (or the weak force???):

Basic

Strongly attractive

Repulsive at short

Observed short range

Charge indep

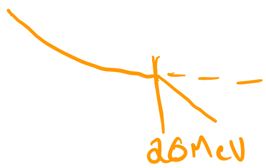
Woods-Saxon (proton-Coloumb)

Binding energy

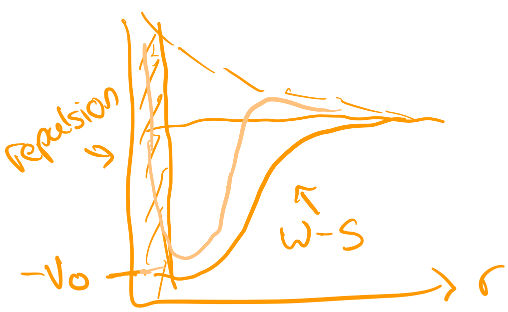
B/A vs. A

Fusion & Fission

Charge symm



$$V(r) = -\frac{V_0}{1+e^{(r-R)/a}}$$



$R = r_0 A^{1/3}$

$r_0 \sim 1{,}25\,\mathrm{fm}$