Weak Interaction.

It is the mechanism of interaction between sub-atomic particles that causes radioactive decay. The weak interaction takes place only at very small sub-atomic distance, less than the diameter of a proton.

An interaction occurs when two particles, typically but not necessarily half-integer spin fermions, exchange integer-spin force carrying bosons.

quantum flavordynamics
↳ weak interactions
quantum chromodynamics
↳ strong interaction
quantum electrodynamics
↳ electromagnetic force.

The fermions involved can either be elementary (eg. electrons, quarks) or composite (protons, neutrons) although, at deepest level, ultimately all interactions are between elementary particles.

Fermions can exchange 3 types of force carriers : W^+, W^-, Z bosons

The mass of each of these bosons is far greater than the mass of a neutron or proton which is consistent with the short range of the weak force.

[It is termed 'weak' interaction as its field strength is several orders of magnitude less than strong nuclear force or electromagnetic force.]

The weak interaction is unique in that it allows for quarks to swap their flavor for another. The swapping of those properties is mediated by the force carrier bosons.

eg. β^- decay : down quark within a neutron is converted into an up quark, thus converting the neutron to a proton with the emmission of an electron and an electron antineutrino.

The weak interaction is the only fundamental interaction that breaks parity-symmetry and charge-parity symmetry.

↓ laws of physics should stay the same if charges are swapped.

parity-symmetry ↓ laws of physics should stay the same under parity swap < ~~mirror~~ switching left to right

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} \quad \det. = -1$$

Parity conservation is respected by : gravitation, electromagnetism & strong interaction.

Sterile
neutrino

properties of weak Interactions

- It is mediated (propagated) by force carrier particles (Gauge boson) that have Significant masses, an unusual feature which is explained ~~by~~ in the Standard Model by the Higgs Mechanism
- Weak interactions affect affect all fermions, the Higgs boson; neutrinos interact through gravity and weak interaction only
  The weak interaction does not produce bound States nor does it involve binding energy, something gravity does on an astronomical scale.

(carries fundamental interactions of nature)

(Elementary particles whose interactions are described by the gauge theory interact with each other by exchange of gauge bosons - usually as virtual particles).

Interaction types

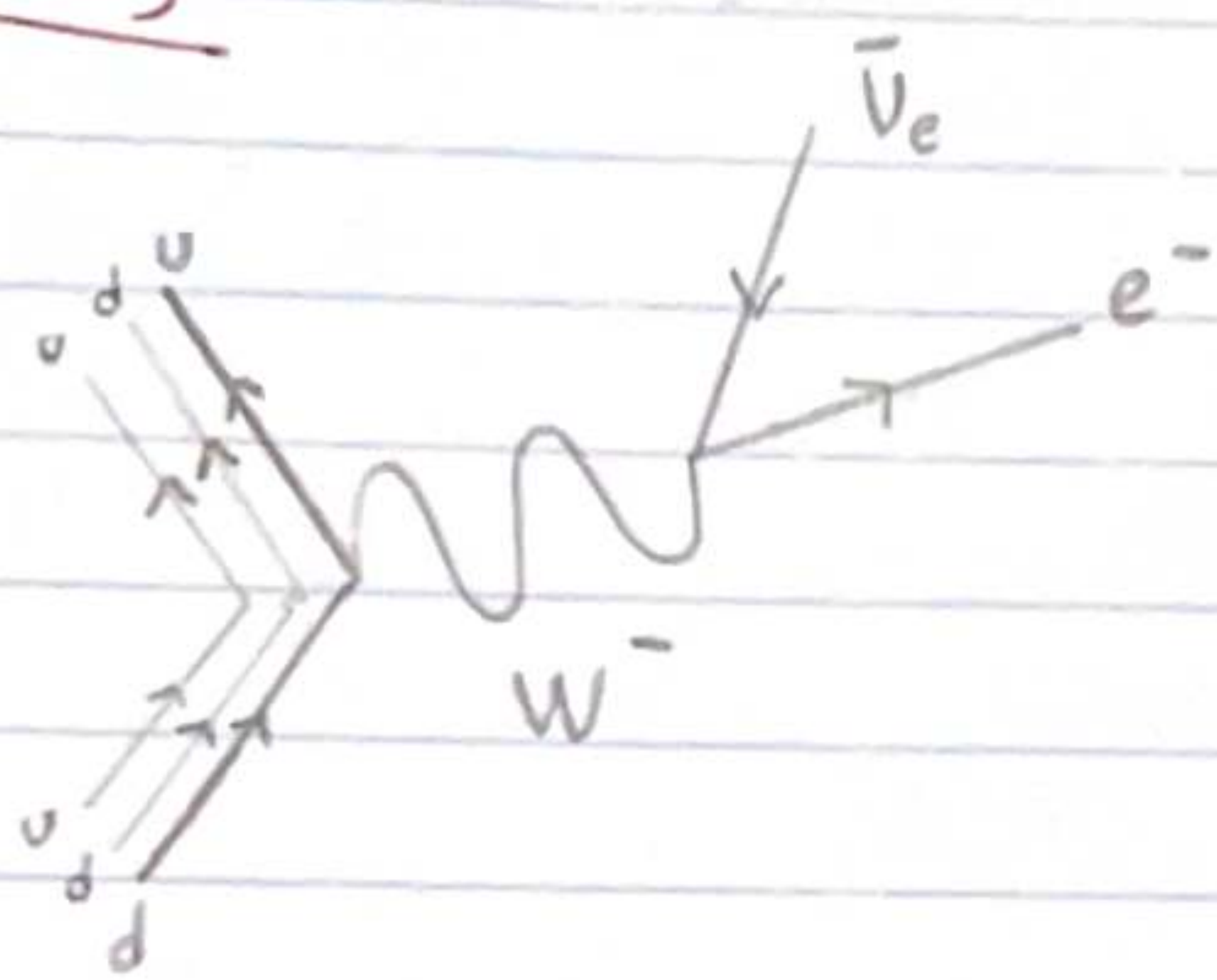
There are two types (also called Vertices)

① Charged-current interaction - Responsible for beta decay phenomenon
- Mediated by particles that carry an electric charge (W^+ or W^- bosons)

② Neutral current Interaction - Mediated by neutral particle - Z bosons

Charged - Current Interaction

β^- - decay



Feynman diagram for β^- decay of n into p, electron and electron antineutrino via an intermediate heavy W^- boson

A down-quark (d) with charge $-\frac{1}{3}$ can ~~absorb a W^+~~ be converted to an up-quark ~~by~~ with charge $+\frac{2}{3}$ ~~with~~ by emitting a W^- boson or by absorbing a W^+ boson

eg. $\mu^- + W^+ \rightarrow \nu_\mu$

↖ Note: In another type of Interaction, a charged lepton (electron or muon) can absorb a W^+ boson (particle with +1 charge) and be thereby converted to a neutrino with charge 0 where the flavor of the neutrino is same as the type of lepton in the interaction

$$d \rightarrow u + W^-$$

$$-\frac{1}{3} \rightarrow +\frac{2}{3} - 1 = -\frac{1}{3}$$

$$d + W^+ \rightarrow u$$

$$-\frac{1}{3} + 1 \rightarrow \frac{2}{3}$$

The W boson is ~~so~~ unstable, so, it will rapidly decay within a very short ~~life t~~ life time

$$W^- \rightarrow e^- + \bar{\nu}_e$$

$$W^+ \rightarrow e^+ + \nu_e$$

For β^- decay

$n \rightarrow p$

Mathematics

$W^+ = -W^-$

$ud(d) \rightarrow ud(u)$

$d \rightarrow u$

emmission of W^-

$d \rightarrow u + W^-$

↳ decays into $e^- + \bar{\nu}_e$

$\Rightarrow d \rightarrow u + e^- + \bar{\nu}_e$

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

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

Spin : $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$?? X

$d \rightarrow u + e^- + \bar{\nu}_e$

$\frac{1}{2} = \frac{1}{2} \quad \frac{1}{2} + \frac{1}{2}$??

Note : Spin cannot be added by Simple arithmetic then spin of neutron is conserved.

→ p - Symmetry problem

Electron and antineutrino are fermions, ~~spin~~ spin-$\frac{1}{2}$ objects, therefore, they may couple to total $S = 1$ (Parallel) or $S = 0$ (anti Parallel)

For antineutrino spin to $= -\frac{1}{2}$ it must be ~~anti~~parallel to electron line of ~~ie.~~ ~~clockwise~~ action of momentum.

P-symmetry violation — gluons
Strong interaction — Fermion, Boson, Baryon... Lepton
Addition of spin — Spin 'detect'
Anti-neutrino chirality — ~~Charge 'detect'~~ W^+ [illegible]
Feynman diagram — emmission/absorbtion of W
α - decay
β^+ decay
γ - decay
virtual particles

β^+ decay

$p \rightarrow n + e^+ + \nu_e$

$uud \rightarrow udd + e^+ + \nu_e$

$u \rightarrow d + e^+ + \nu_e$

Charge must be conserved

$u \rightarrow d + W^+$

$+\frac{2}{3} = -\frac{1}{3} + 1 \qquad \frac{2}{3} = \frac{2}{3}$

$W^+ \rightarrow e^+ + \nu_e$

$+1 \qquad +1 \quad +0$

$u \rightarrow d + e^+ + \nu_e$ *

~~$+\frac{2}{3} = -\frac{1}{3} + \frac{1}{2}$~~ (n & P) have 3 fermions (baryon)

~~$+\frac{2}{3} = +\frac{2}{3} + \frac{6}{3}$~~ $\quad$ ~~$+\frac{2}{3} = -\frac{1}{3} + \frac{1}{2} = -\frac{2}{6} + \frac{3}{6}$~~

* $u \rightarrow d + e^+ + \nu_e$

$\frac{2}{3} = -\frac{1}{3} + 1 + 0$

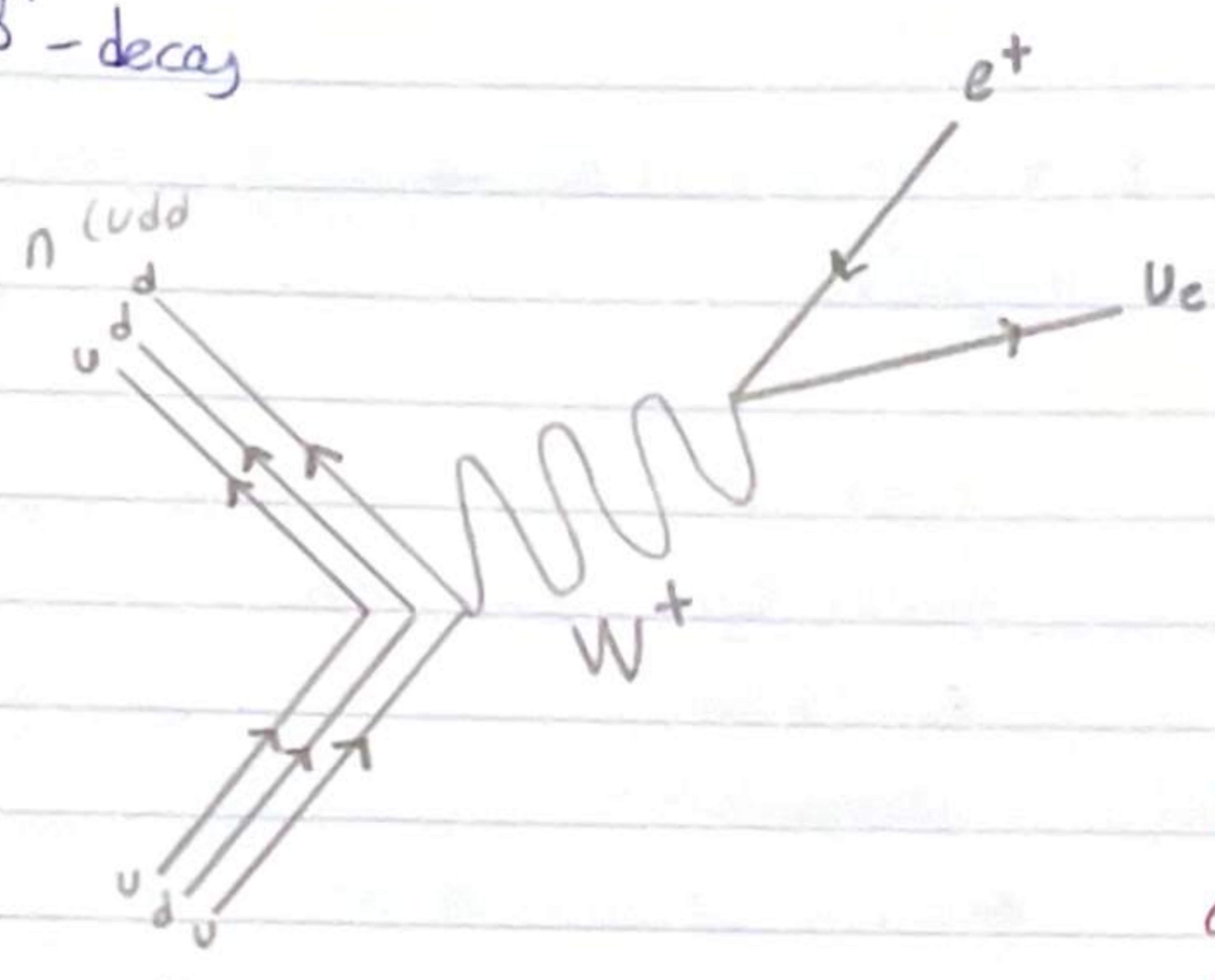
$\frac{2}{3} = \frac{2}{3}$ (Charge conserved)

$d \rightarrow u + e^- + \bar{\nu}_e$

$-\frac{1}{3} = \frac{2}{3} - 1 + 0$

$-\frac{1}{3} = -\frac{1}{3}$ (Charge conserved)

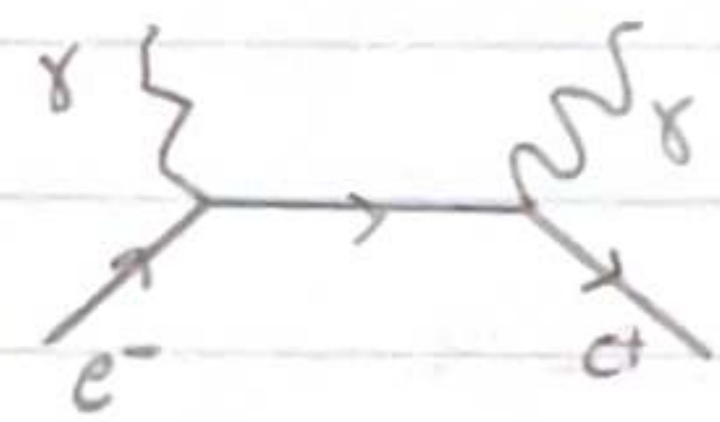
β^+ - decay



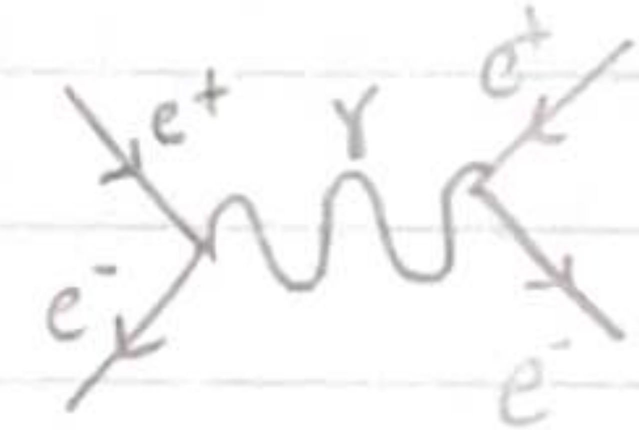
Note annihilation:
particle colliding with its corresponding anti-particle to
eg: e^- & e^+ produce 2 photons
(gamma

~~Weak~~

Fundamental force	Force carrier
Weak nuclear	Bosons (W^+, W^-, Z)
Strong nuclear	gluons
~~El~~ Electromagnetic	photon
Gravity	?? (Graviton ??)



or



arrow direction as convention of signs
vertices cannot have arrows pointing in same direction
(a vertex has only 2 arrows (or 1))

α - decay is explained by mechanisms not involving weak force ??
but by Strong nuclear & electromagnetic

~~Strong Interactions~~

Classification of Elementary particles

- Boson - particle that follows Bose-Einstein Statistics
  eg. photons, gluons, W and Z bosons (the 4 force carrying gauge bosons of the universe.) (also Higgs boson and hypothetical graviton)

- Fermion - particle that follows Fermi-Dirac Statistics
  eg. Include all quarks and leptons as well as composite particles made of an odd number of these, such as all baryons and many atoms and nuclei
  A fermion can be an elementary particle such as the electron or it can be a composite particle such as the proton.

Bosons have integer spin while fermions have half-integer spin.

- quarks - Elementary particle and a fundamental constituent of matter

- Hadron is a composite particle made of quarks held together by the strong force
  ↳ (classified into) baryons and mesons

- baryons - made of 3 quarks (Proton and neutrons)

- mesons - made of one up quark and one antiquark (pion)

- Lepton - elementary particle with $\frac{1}{2}$ integer spin that does not undergo strong interactions

Two main type of leptons → Charged leptons → electron, muon, tau

→ Neutral leptons → electron neutrino, muon neutrino, tau neutrino.

Elementary particles are particles with no measurable internal structure.

Fermions ← Elementary → Bosons

Fermions → Quarks, leptons

Bosons → Photon, W, Z, Gluon, Higgs

Composite particles

Hadrons → 3 quarks → proton & neutron (baryons) → (composite fermions)

Hadrons → 1 quark & 1 anti-quark → Meson → pion

quantum number:

- Spin
- Colour
- Strangeness
- angular Momentum
- Charge
- mass

Strong Interactions

It is the mechanism responsible for Strong nuclear force.
At a range of 1 femtometer (10^{-15} m), Strong force is approximately 137 time as Strong as electromagnetism, million time Stronger than weak interactions and 10^{38} time Stronger than gravitation.
The Strong nuclear force holds most matter together because it ~~hold~~ Confines quarks into hadron particles Such as protons or neutrons. In addition, the Strong nuclear force binds neutrons and protons ~~into~~ to create atomic nuclei. Most of the mass of a common proton or neutron is the result of Strong force field energy, the individual quarks provide only about 1% of the mass of a proton.

$1eV = 1.6 \times 10^{-19}$ J

$E = qV$ (↑ electronic charge, ↑ 1 volt)

$E = eV$

[J]

$E = mc^2$

$m = \frac{E}{c^2} = \frac{eV}{c^2}$

This force is observable at 2 ranges : on a larger Scale (1-3 fm), it is the force that bind proton and neutron (nucleons) to form the nucleus of an atom.
On the smaller Scale (< 0.8 fm), the radius of a nucleon, it is the force (carried by gluons) that hold quarks together to form proton, neutrons and other hadrons. The Strong force inherently has Such a high Strength that hadrons bound by the strong force can produce new massive particles. Thus, if hadrons are Struck by high-energy particles, they give rise to new hadrons instead of emitting freely moving radiation (gluons). This property of Strong force is called colour confinement and it prevents the free "emission" of the Strong force : instead, in practice, jets of massive particles are produced

↓

based on mass - Energy Equivalence

Electrons & neutrinos → unaffected by Strong interaction, but weak nuclear force influences them.

quarks & gluons are affected by Strong nuclear force

quarks are affected by weak nuclear force ??

Q:5

Residual force of quarks binding bind proton and neutrons

In the context of binding protons and neutrons together to form atomic nuclei, the Strong Interaction is called the nuclear force (or residual strong force). In this case, it is the residuum of the Strong interaction between the quarks that make up the protons and neutrons. As such, the residual strong interaction obeys a quite different distance-dependant behaviour between nucleons, from when it is acting to bind quarks within nucleons. Differences in the binding energy of the nuclear force between different nuclei power nuclear fusion and nuclear fission.

The Strong interaction is mediated by the exchange of massless particles called gluons that act between quarks, ~~and~~ antiquarks and other gluons. Gluons are thought to interact with quarks and other gluons by way of a type of charge called colour charge. Colour charge is analogous to electromagnetic charge, but it comes in 3 types (± red, ± green, ± blue) rather than one (Photon??), which result in a different type of force, with different rules of behaviour.

The force carrier particle ~~is~~ of the Strong interaction, is a gluon; (a massless boson). Unlike the photon in electromagnetism, which is neutral, the gluons carry a colour charge.

Quarks and gluons are the only fundamental particle that carry a non-vanishing colour charge and hence they can participate in strong interactions only with each other. The strong force is the expression of the gluon interaction with other quark and gluon particles.

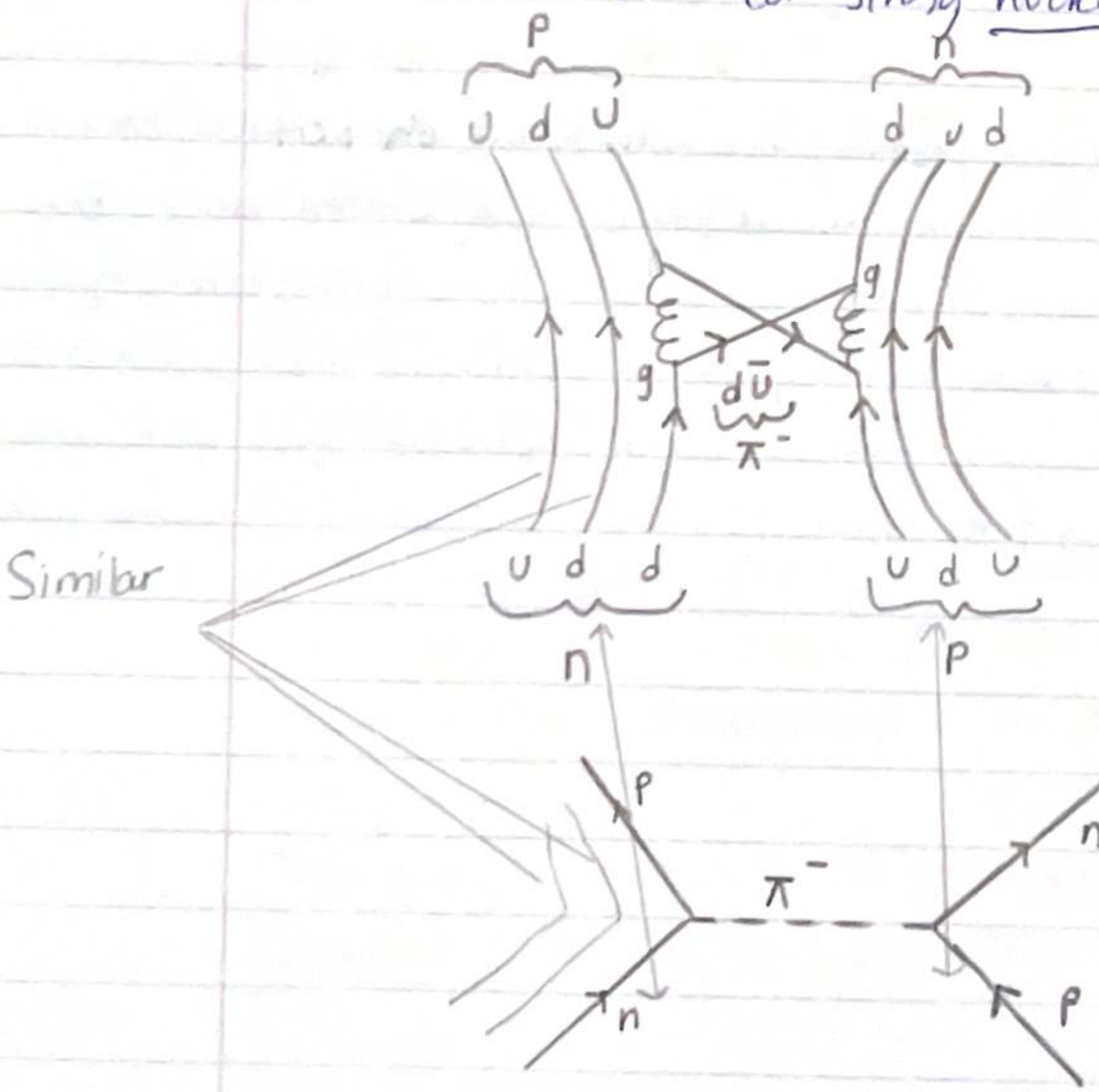
The strength of interaction is parametrised through coupling constant. This strength is modified by the gauge colour of the particle.

The strong force acts between quarks. Unlike all other forces (electromagnetic, weak and gravitational), the strong force does not diminish in strength with increasing distance between pairs of quarks. After a limiting distance (about the size of a hadron) has been reached, it remains at a strength of about 10 000 N no matter how much farther the distance between the quarks. As the separation between the quark grows, the energy added to the pair creates new pairs of matching quarks between the original two; hence, it is impossible to create separate quarks. The explanation is that the amount of ~~force~~ work done against a force of 10 000 N is enough to create particle-antiparticle pairs within a very short distance of the interaction. The very energy added to the system required to pull two quarks apart will create a pair of new quarks that will pair up with the original ones. In QCD, this is called colour confinement; as a result, only hadrons and not free quarks can be observed.

The elementary quark and gluon particles involved in a high energy collision are not directly observable. The interaction produces jets of newly created hadrons that are observable. Those hadrons are created as a manifestation of mass-Energy equivalence, when sufficient energy is deposited in a quark-quark bond (quark of one proton is struck by the very fast quark of an impacting proton in particle accelerator). (However, quark-gluon plasmas have been observed.) → free quarks?? (free from hadron)?? (no colour confinement)

analogy to e^- & plasma

Every quark in the universe does not attract every other quark in the distant-independant manner, since colour confinement implies that the strong force acts without distance-diminishment only between pairs of quarks, and that in collection of bound quarks (hadrons) the colar of the quark cancel out resulting in a limit of the action of the forces. Collection of quarks therefore appear nearly without colour charge and the strong force is nearly absent between those hadrons except the cancellation is not quite perfect, a residual force remains, known as the residual strong force. This residual force does diminish rapidly with distance and is thus very short-range (few fms). It manifests as a ~~fource~~ force between the 'colourless' hadrons and is known as the nuclear force (or strong <u>nuclear</u> force)



(Hadron - Hadron interaction via residual strong force.

(meson mediated)

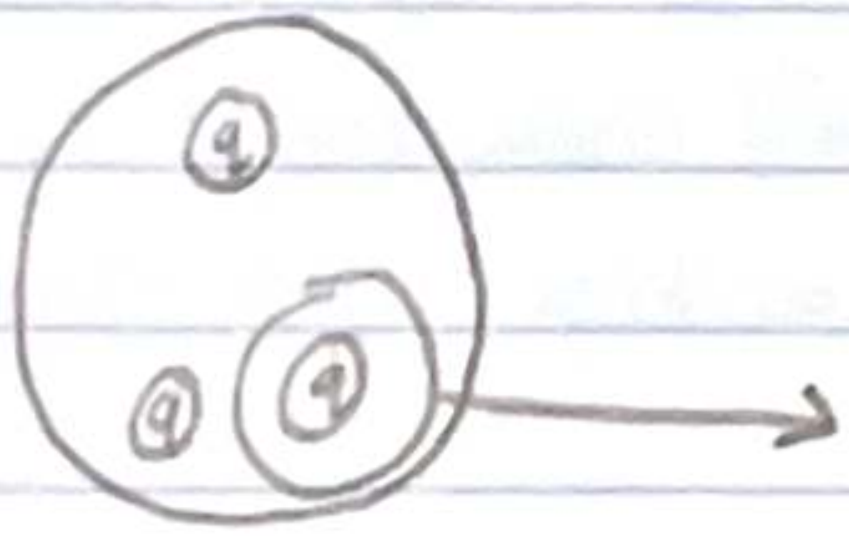
π^- : $d\bar{u}$
π^0 : $d\bar{d}$ $u\bar{u}$
π^+ : $u\bar{d}$

??

Colour confinement

In QCD, Colour confinement is the phenomenon that colour charged particles (quarks & gluons) cannot be isolated and therefore cannot be directly observed in normal conditions below the Hagedorn temperature of approximately 2 trillion kelvin (130-140 MeV per particle). Quarks and ~~hadrons~~ gluons cannot be separated from their parent hadron without producing new hadrons.

Limited range of the Strong interaction.



Consider this hadron

If we take out this quark, another one would be generated in the hadron due to colour confinement therefore considering the hadron, the action of the Strong force is limited (to the radius of the hadron)

~~The Separation independent force does~~

The Separation-independent force between 2 quarks does occur theoretically when the quarks, being in a hadron, is not considered, but practically this is not the case due to colour confinement and existence of hadrons (quarks occurring in clusters)

Note: 3 quarks - baryon } hadron
1 quark, 1 antiquark - Meson }

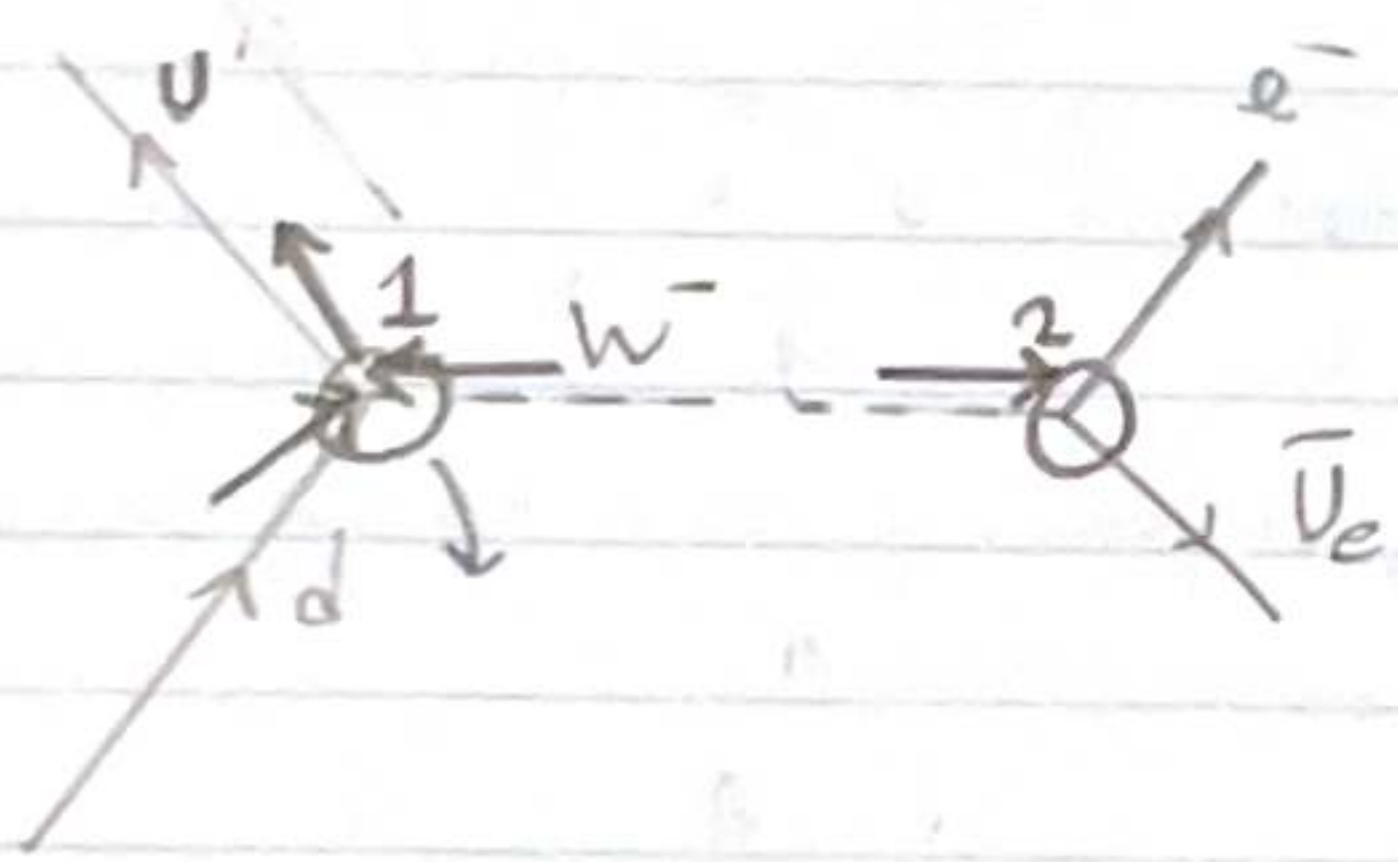
interact

Virtual particles → All force carriers are virtual particles during ^ [interact]

- It is a transient fluctuation that exhibits some characteristics of an ordinary particle but whose existance is limited by the uncertainty principle.
- Represented by internal lines in feynman diagrams.
- They do not necessarily carry the same mass as the corresponding real particle although, they always conserve energy and momentum.
- Does not precisely obey energy-momentum relation.
- Quantum tunelling may be considered as a manifestation of virtual particle exchanges. The range of forces carried by ~~the~~ virtual particles is limited by the uncertainty principle which regard energy and time as conjugate variables; thus virtual particles of larger mass have more limited range.

"Rapid decay"

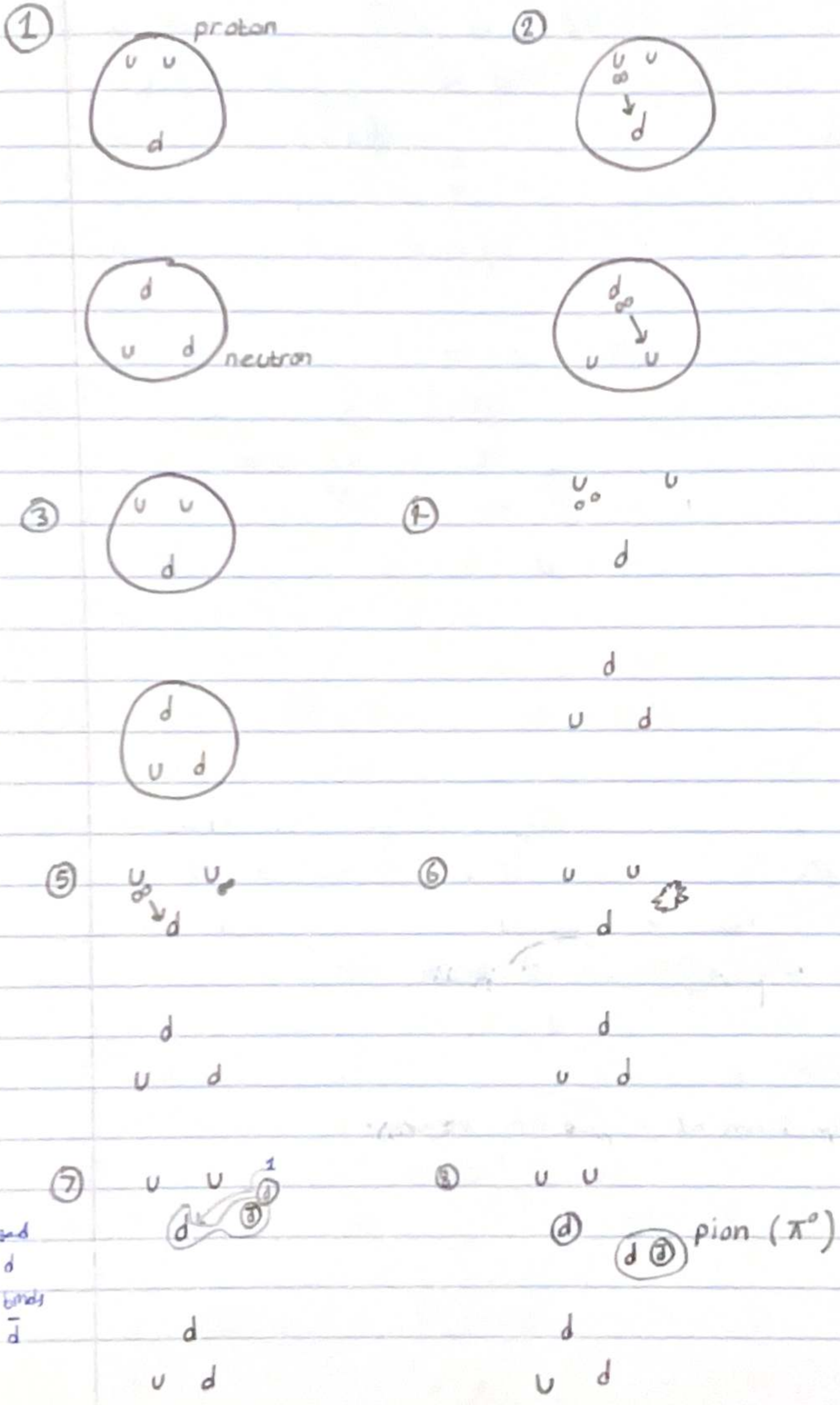
Feynman diagram



2: Interaction release e^- & $\bar{\nu}_e$ (W^- "decay")

1: Interaction of d and W^- release U

* Pions mediating residual strong interaction (nuclear force)



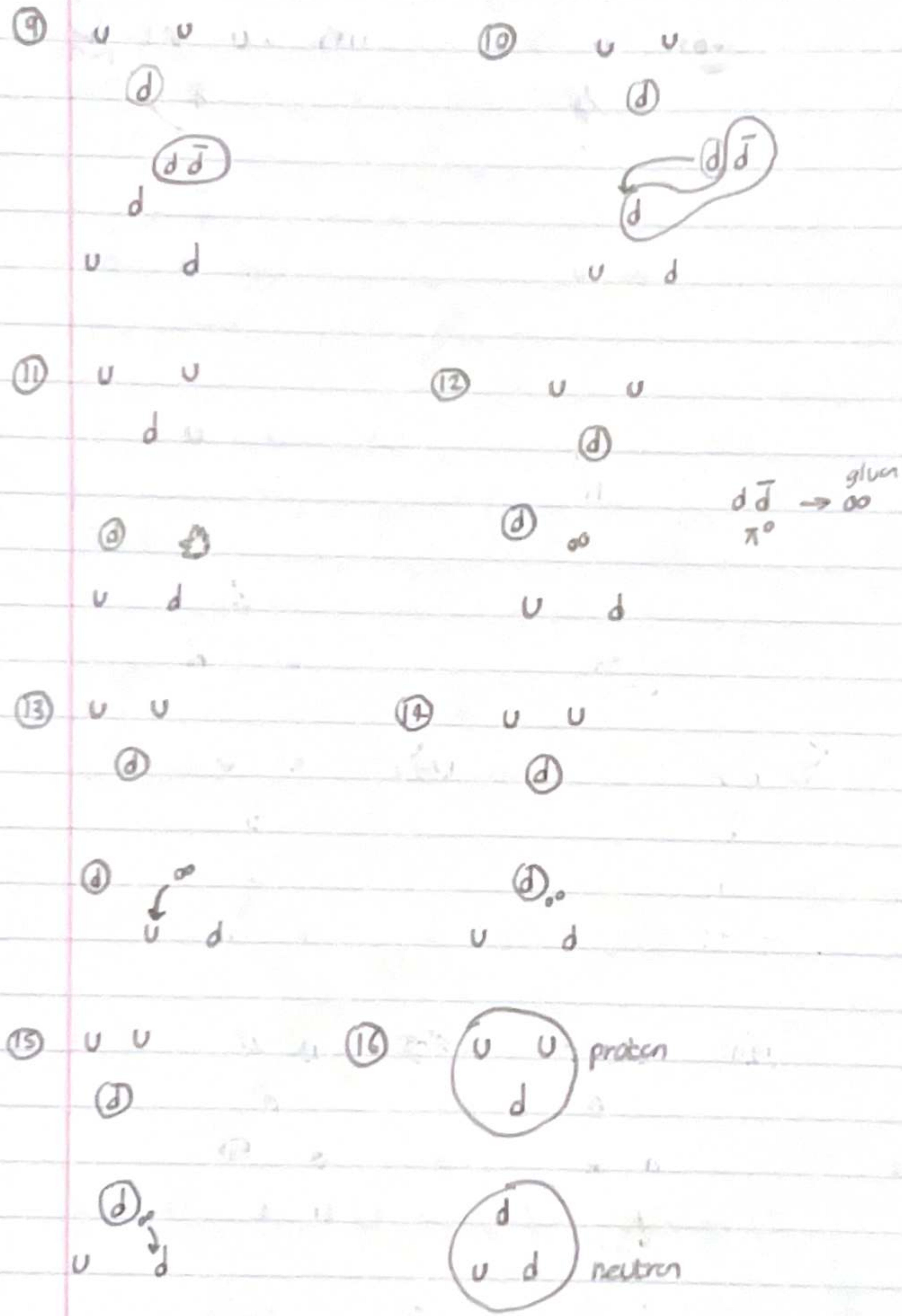
$T = \frac{\text{time}}{\text{no. osc.}}$

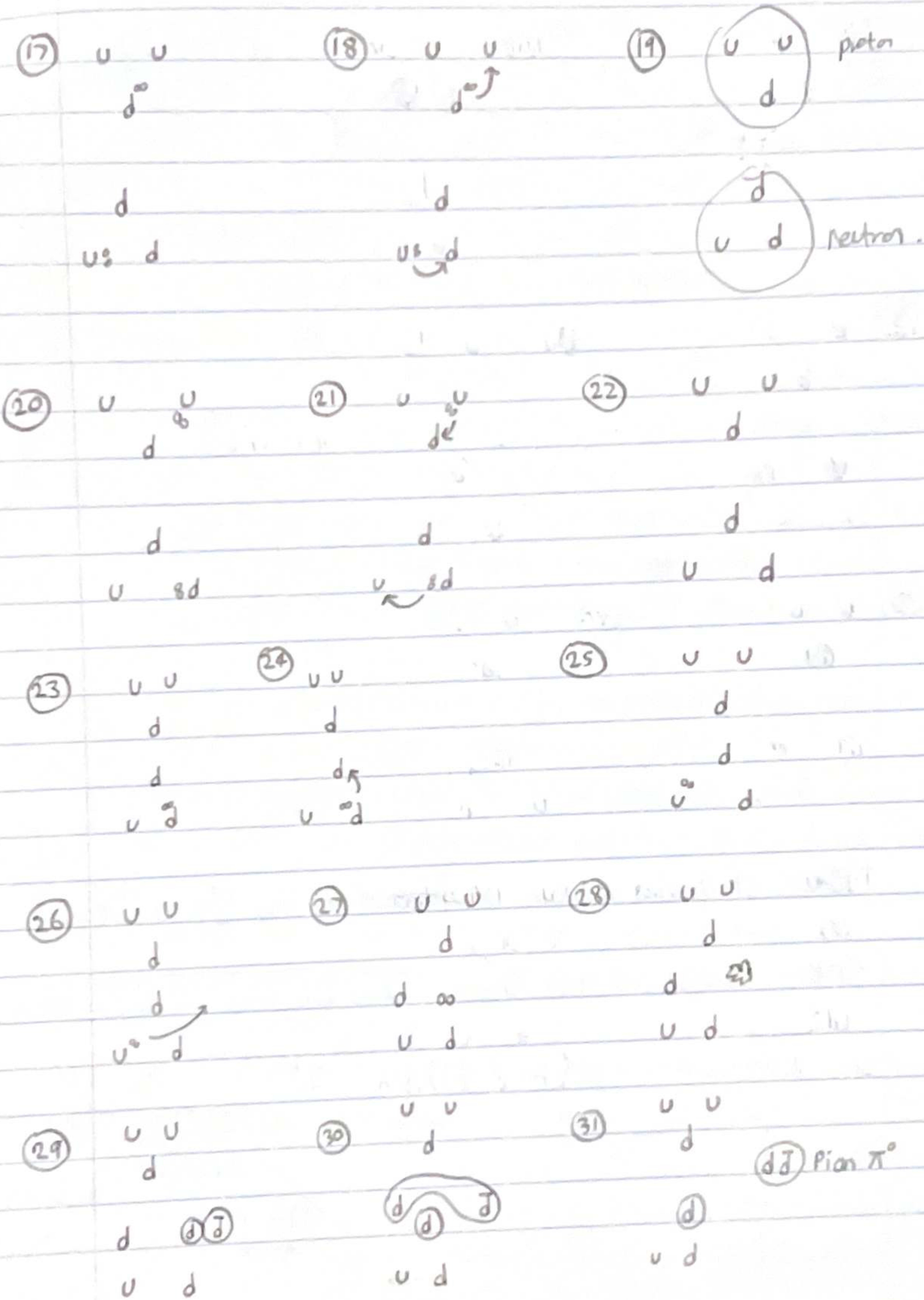
1 replaced $\bar{d}$ for d and d binds with $\bar{d}$

$\ln x = e^2$
$x = e^{e^2}$

$\ln x = 3$
$x = e^3$

$e^{\ln x} = e^3$
$\ln x\, e = e^3$
$x \ln e = e^3$
$x = e^3$





17
18
19
proton
Neutron.
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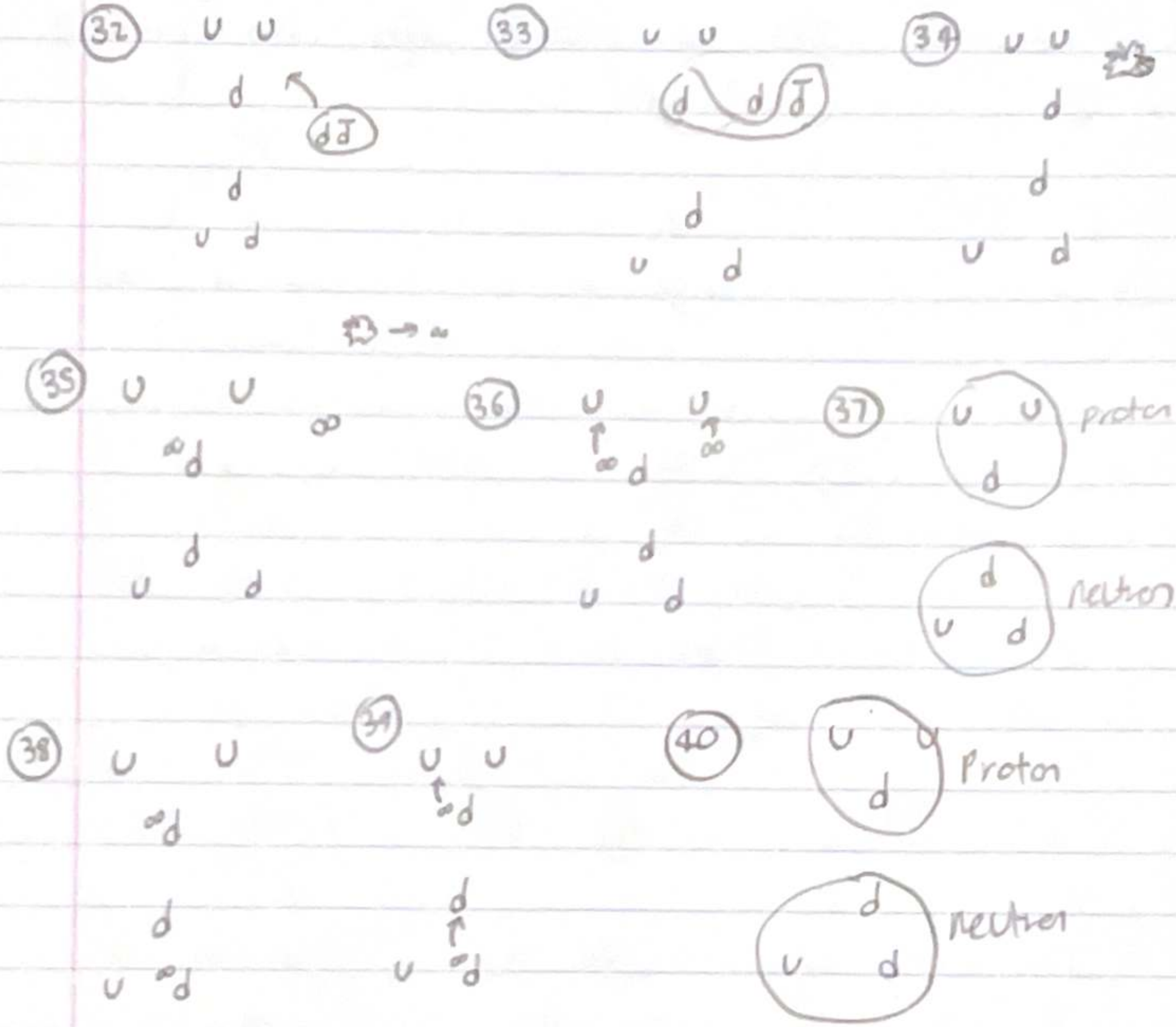
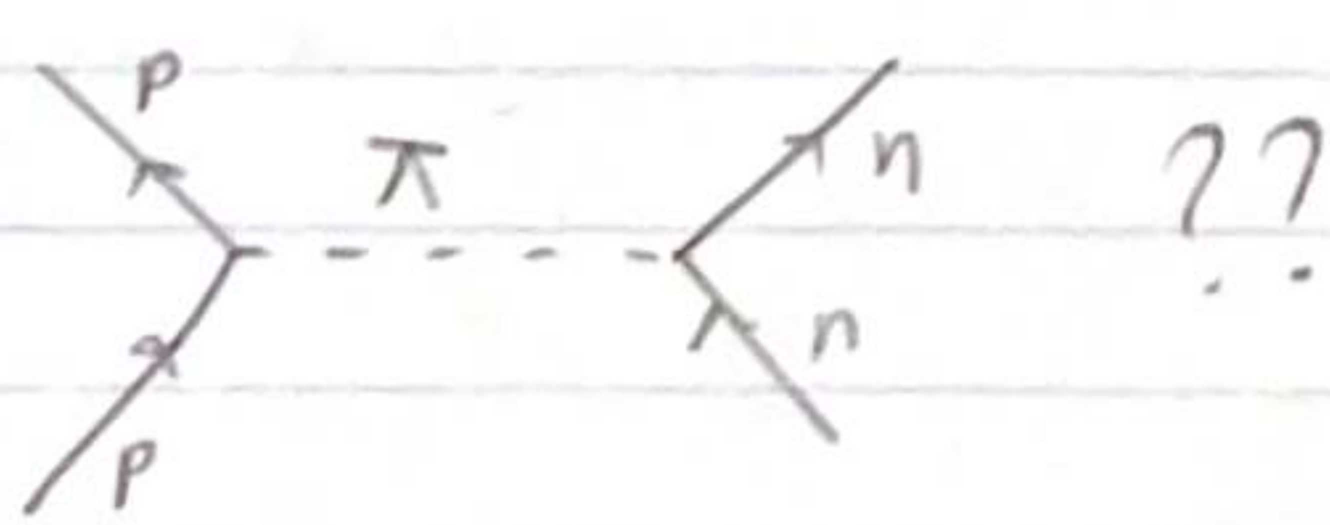
Pion π°

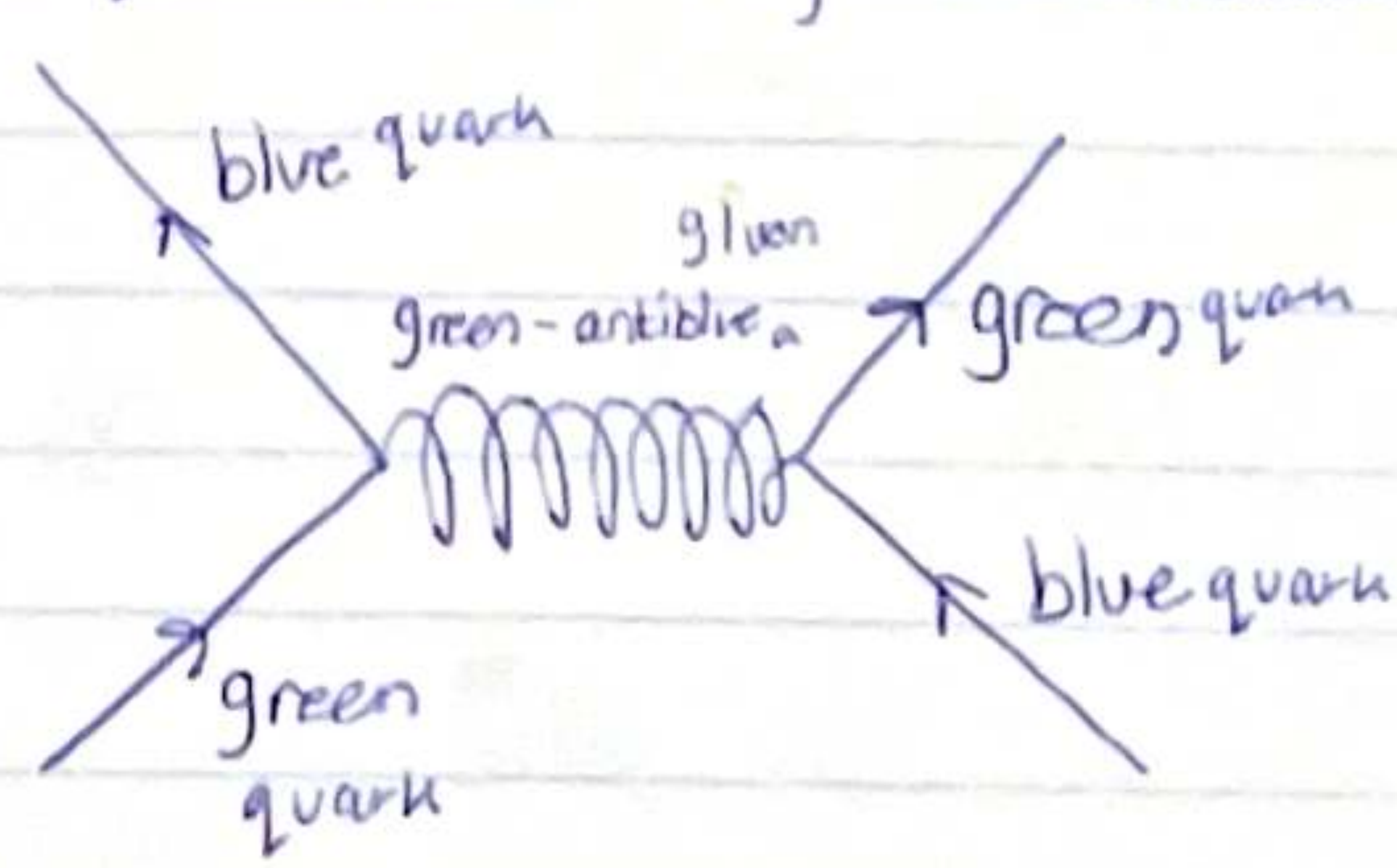


flavors of quarks remain unaffected during Strong Interaction.

Colour charges are not shown



Quark-quark interaction via strong force (Gluon mediated)



Quark - quark interaction via Strong force. (Gluon mediated)