The particle zoo

Known particles that behave like matter:
proton, neutron, electron, electron-neutrino, positron, electron anti-neutrino
Known particles that behave like forces:
photon (E-M force), W^+ & W^- bosons (weak nuclear force)

↑ Zero mass
Infinite range

↑ Huge mass
0.001 fm
Changing momentum by changing mass, $p=mv$, $E=mc^2$

Strong nuclear force?

Proposed particle mediating the SNF, pion?
Used particle detectors (cloud chambers) to detect particles created when cosmic rays strike atmosphere.
Accidentally discovered muon (μ) ← same as electron except 200x more massive!
Accidentally discovered kaon (K) ← charged mass larger than proposed pion, smaller than proton

Discover pions! medium masses

Zoo contains: $p, n, e^-, e^+, \nu_e, \bar{\nu}_e, \mu^-, \mu^+, \pi^+, \pi^0, \pi^-, K^+, K^0, K^-, \bar{K}^0, \gamma, W^+, W^-, Z^0$

Kaons?

Strange particles — longer than expected half-life*
* time for half of particles to decay
Decayed via weak interaction

Conservation rules

"Energy-mass" always conserved $E=mc^2$
Momentum always conserved
Charge always conserved

Particle Sorting

$E=mc^2$

Name	Charge/ proton charge	Rest Energy/ MeV	Interacts
p	+1	938	S, W, EM
n	0	939	S, W
e^-	-1	0.511	W, EM
ν_e	0	0	W
π^+	+1	140	S, W, EM
π^0	0	135	S, W,
π^-	-1	140	S, W, EM
K^+	+1	494	S, W, EM
K^0	0	498	S, W,
K^-	-1	494	S, W, EM
μ^-	-1	106	W, EM

ANTIPARTICLES

$\bar{p}$

$\bar{n}$

e^+

$\bar{\nu}_e$

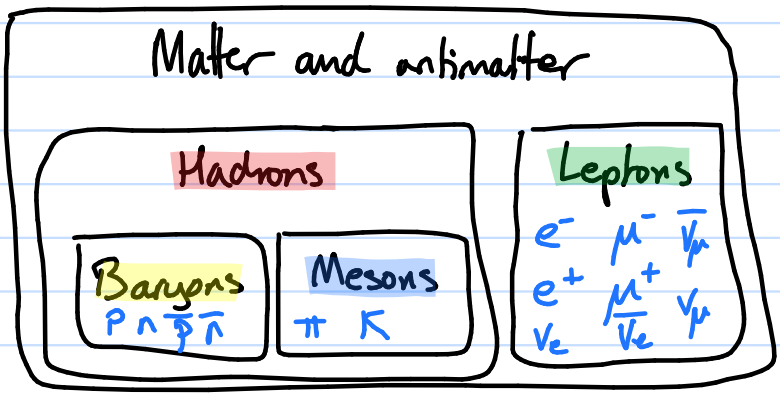
maybe π^- and π^+
K^- and K^+
one particle, one antiparticle?

μ^+

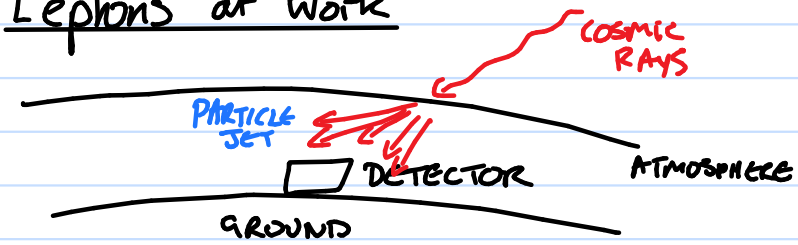
Particles that interact with SNF, HADRONS
Particles that do not interact with SNF, LEPTONS

π decay by WNF (Weak Nuclear force) but not into protons
n decay by WNF into protons
p don't decay — they are stable
K decay by WNF but not into protons

Baryons are hadrons that decay into protons
Mesons are hadrons that do not decay into protons



Leptons at work

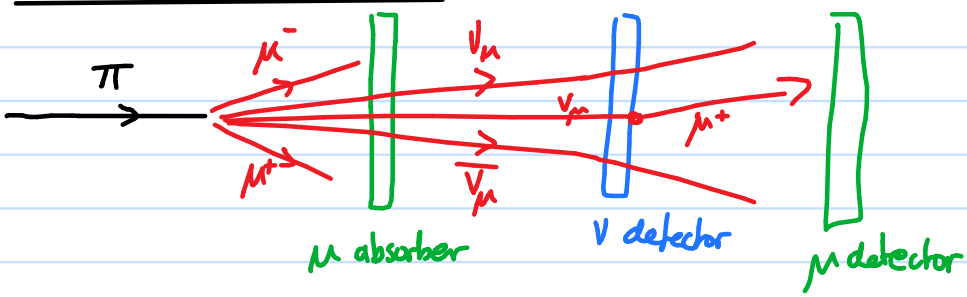


electron neutrino ν_e — electron antineutrino $\bar{\nu}_e$

muon neutrino ν_μ — muon antineutrino $\bar{\nu}_\mu$

(tau neutrino ν_τ — tau antineutrino $\bar{\nu}_\tau$) NOT ON A-LEVEL

DETECTION OF NEUTRINOS



$\nu_e + n \xrightarrow{W^{+-}} p + e^-$ IS OBSERVED

$Q: 0 + 0 = +1 + -1$ ✓

matter → $\nu_e + n \not\rightarrow \bar{p} + e^+$ ← antimatter IS NOT OBSERVED

$Q: 0 + 0 = -1 + 1$ ✓

$(L_e: 1 + 0 = 0 + -1$ ✗)

$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$ IS OBSERVED

$\mu^- \not\rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$ IS NOT OBSERVED (WE NEVER GET MATTER CHANGING INTO ANTIMATTER)

Lepton number a property leptons have and it is always conserved

e^- : $L_e = 1$: $Q = -1$

e^+ : $L_e = -1$: $Q = +1$

ν_e : $L_e = 1$: $Q = 0$

$\bar{\nu}_e$: $L_e = -1$: $Q = 0$

We conserve muon lepton numbers separately

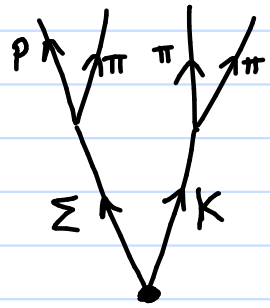
μ^- : $L_\mu = 1$: $Q = -1$

μ^+ : $L_\mu = -1$: $Q = +1$

ν_μ : $L_\mu = 1$: $Q = 0$

$\bar{\nu}_\mu$: $L_\mu = -1$: $Q = 0$

Quarks and antiquarks



Σ (baryons) and K (mesons) have "strangeness"

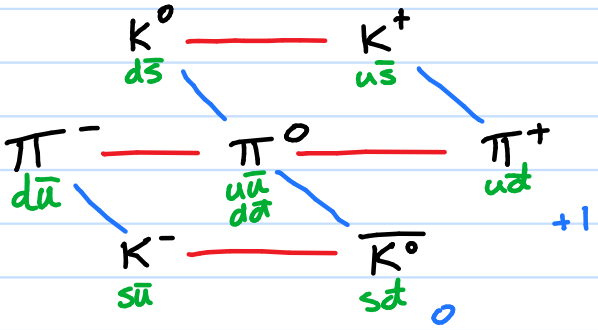
K^+ has strangeness of +1
K^- has strangeness of −1
K^0 has strangeness of +1
$\overline{K^0}$ has strangeness of −1

1: $\pi^- + p \longrightarrow K^+ + \Sigma^-$ ✓ is observed
2: $\pi^- + n \longrightarrow K^- + \Sigma^0$ ✗ not observed
3: $\pi^+ + n \longrightarrow K^+ + \Sigma^0$ ✓ is observed
4: $\pi^- + n \longrightarrow K^0 + \Sigma^-$ ✓ is observed

Σ^+ strangeness of −1
Σ^0 strangeness of −1
Σ^- strangeness of −1

strangenesses
1: 0 + 0 ⟶ +1 + −1 ✓
2: 0 + 0 ⟶ −1 + −1 ✗
} Can create equal amounts of +ve & −ve strangeness

IN STRONG INTERACTIONS, STRANGENESS IS CONSERVED
IN WEAK INTERACTIONS, STRANGENESS IS NOT CONSERVED
→ CALLED DECAYS SOMETIMES



STRANENESS
+1
0
−1

MESONS
NOT FUNDAMENTAL!
CONTAIN 1 QUARK + 1 ANTIQUARK

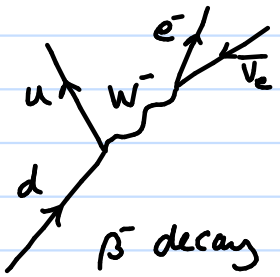
CHARGE −1

Quarks & antiquarks

	up (u)	down (d)	strange (s)	$\bar{u}$	$\bar{d}$	$\bar{s}$
Charge Q	2/3	−1/3	−1/3	−2/3	1/3	1/3
Strangeness S	0	0	−1	0	0	1
Baryon number B	1/3	1/3	1/3	−1/3	−1/3	−1/3

all reversed

proton = uud
neutron = udd
sigma$^+$ = uus
sigma^0 = uds
sigma$^-$ = dds



Conservation rules

Conserved in all interactions: Q (charge), B (baryon number), L_e (electron lepton number), L_μ (muon lepton number), L_τ (tau lepton number)

Conserved in all interactions EXCEPT WEAK: S (strangeness), C (charm), T (topness), b (bottomness)

Weak interactions are the only interactions that can change the quark type.

Leptons do not interact with the Strong Nuclear Force

More from the zoo

$\Lambda^0 = uds \neq \Sigma^0 = uds$
$\Delta^+ = uud \neq p = uud$
$\Delta^0 = udd \neq n = udd$
$\Delta^- = ddd$
$\Delta^{++} = uuu$
$\Sigma^+ = uus$
$\Sigma^- = dds$
$\Xi^0 = uss$
$\Xi^- = dss$
$\Omega^- = sss$

① $p + \bar{p} \longrightarrow \pi^+ + \pi^-$

Q: $1 + (-1) = 1 + (-1)$ ✓
B: $1 + (-1) = 0 + 0$ ✓
L_e: $0 + 0 = 0 + 0$ ✓
L_μ: $0 + 0 = 0 + 0$ ✓

} is observed

①: $uud + \bar{u}\bar{u}d \longrightarrow ud + d\bar{u}$

u: $2 + (-2) = 1 + (-1)$ ✓
d: $1 + (-1) = -1 + 1$ ✓

② $p + \bar{p} \longrightarrow p + \pi^-$

Q: $1 + (-1) = 1 + (-1)$ ✓
B: $1 + (-1) \neq 1 + 0$ ✗

} not observed

②: $uud + \bar{u}\bar{u}d \longrightarrow uud + d\bar{u}$

u: $2 + (-2) = 2 + (-1)$ ✗
d: $1 + (-1) = 1 + 1$ ✗

Beta decay

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

Q: $0 = 1 + (-1) + 0$ ✓
B: $1 = 1 + 0 + 0$ ✓
L_e: $0 = 0 + 1 + (-1)$ ✓

$udd \longrightarrow uud + e^- + \bar{\nu}_e$

u: $1 = 2 + 0 + 0$
d: $2 = 1 + 0 + 0$

} d → u WEAK

$\Sigma^0 \longrightarrow p + \mu^- + \bar{\nu}_\mu$

uds → uud (s → u)

Q: $0 = 1 + (-1) + 0$ ✓
B: $1 = 1 + 0 + 0$ ✓
L_μ: $0 = 0 + 1 + (-1)$ ✓
$M_{LHS} > M_{RHS}$ ✓

$p \longrightarrow \Sigma^0 + \mu^+ + \nu_\mu$

uud → uds (u → s)

Q: $1 = 0 + 1 + 0$ ✓
B: $1 = 1 + 0 + 0$ ✓
L_μ: $0 = 0 + (-1) + 1$ ✓
$M_{LHS} < M_{RHS}$ ✗

Energy is conserved, mass is treated as a "type" of energy → Decays work to spread out the energy