Announcement

- Homework (10%) + Class participation (10%)
- HW6 due: 03/15
- Midterm 1 (20%) + Midterm 2 (20%)
- Final (40%) on 3/22, Fri, 12-3 pm, 235 ISB
  - Bring calculator, open-book and open-notes
  - 30% Nuclear
  - 30% Elementary
  - 40% Atomic, statistical, and solid state focusing on common underlying ideas:
    - Energy, Hamiltonian, conservation, system, etc.

Grade ranges

- 95 <= A+
- 90 <= A < 95
- 87 <= A- < 90
- 84 <= B+ < 87
- 80 <= B < 84
- 77 <= B- < 80

Review session

- 3/18, Mon: 9 am to 2 pm
- 3/19, Tues: 3-5 pm
- 3/20, Wed: 9 am – 12 pm
- 3/21, Thurs: 9 am – 5 pm

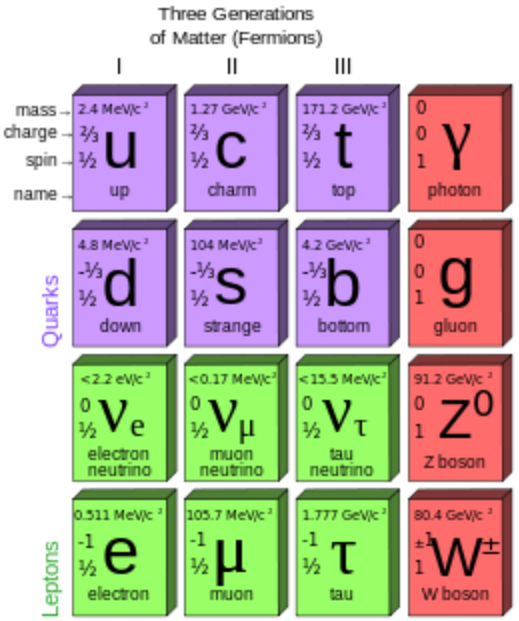
Lecture 19 Topics

- Particles/anti-particles
- Forces
- Symmetry and conservation
- Conservation rules in elementary particle decay
- Feynman Diagram

Elementary particles

What are the fundamental building blocks of the Universe (living and nonliving)?

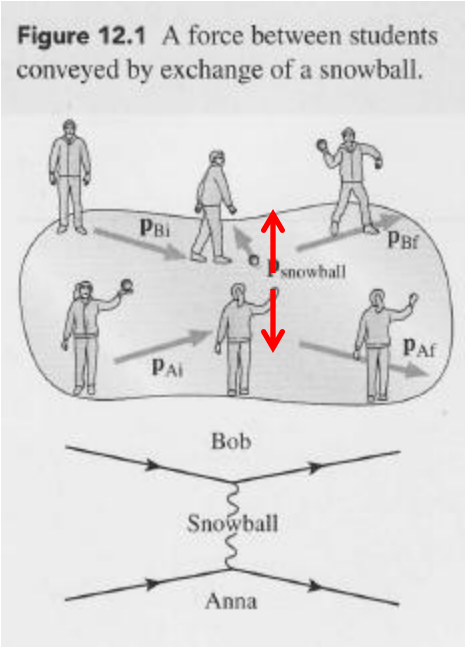
-Molecules
-Atoms → Elements
-Nucleus + electrons
-Nucleons (protons and neutrons) in the nucleus
-Quarks in nucleons



Three classes of particles:
- Six quarks → strong force
- Six leptons → electroweak force
- Four mediating particles called field quanta
  - → Graviton: gravitational force
  - → Photon: electromagnetic force
  - → W^+, W^-, Z^0: weak force
  - → Gluon: strong force

New definition for force

Force is exerted by exchanging a mediating particle.



Anna is throwing a snowball on a frictionless frozen pond.

$$\vec{p}_{Anna\,(after\ snowball\ throwing)} = \vec{p}_{Anna} - \vec{p}_{snowball}$$

$$\vec{p}_{Bob\,(after\ snowball\ receiving)} = \vec{p}_{Bob} + \vec{p}_{snowball}$$

Limitations of snowball analogy:
-Attractive fundamental force cannot be shown
-Mediating particles exist during the exchange, not before or after
-Mediating particles do not act like snowball (classical physical entities)

Force range

From uncertainty principle

$$\Delta t \Delta E \approx \hbar \longrightarrow \Delta t \approx \frac{\hbar}{\Delta E}$$

Energy of the mediating particle

$$\Delta E = mc^2$$

$$\Delta t \approx \frac{\hbar}{\Delta E} \approx \frac{\hbar}{mc^2}$$

Force range

$$\Delta x \approx c\Delta t \approx \frac{\hbar}{c}\frac{1}{m}$$

- When the mediating particle has mass
- When it doesn't

Force range

TABLE 12.1 Fundamental forces and particles

Force	Gravitation	Electroweak			Strong	Residual
Property	Mass/energy	Charge/weak charge			Color charge	
Strength	$\sim 10^{-39}$	$\sim 10^{-2}$	$\sim 10^{-6}$		1	
Range	$1/r^2$	$1/r^2$	10^{-3} fm		short	1 fm
Mediating Bosons	Graviton?	Photon, γ	W^+, W^-	Z^0	Gluon	$\pi^{\pm}, \pi^0$
Spin	2?	1	1	1	1	0
Mass	0?	$< 6 \times 10^{-22}$	80.4×10^3	91.2×10^3	< 10	140, 135
Charge	—	0	+1, −1	0	0	$\pm 1, 0$
Color charge	—	—	—	—	r, g, or b + $\bar{r}$, $\bar{g}$, or $\bar{b}$	Neutral

$$\Delta x \approx c\Delta t \approx \frac{\hbar}{c}\frac{1}{m}$$

- When the mediating particle has mass
- When it doesn't

How fundamental forces are connected?

- Particles
  - Fundamental particles experiencing force are fermions
  - Fermions should have a property associated with the force if they are engaged in that force
    - Mass/energy for gravitational force
    - Charge/weak charge for electroweak force
    - Color charge for strong force
- Mediating particles
  - Spin: particles that mediate force are bosons
  - Mass determines the range of the force

Force range

Between quarks

Between Nucleons

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Color charge	—	—	—	—	r, g, or b + $\bar{r}$, $\bar{g}$, or $\bar{b}$	Neutral

$$Y_W = 2(Q - T_3)$$

Weak charge
-2 times (Electrical charge minus weak isospin)

Quarks for Strong force

- Particles that experience strong force are Quarks
- Six types
  - Spin ½
  - Have different mass
  - Have different charge
  - Have all three color charge
  - Have antiparticles
  - Not separable

Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

- Gluons (massless, spin-1) are mediating particles

Color charge

- Three types: red (r), green (g) and blue (b)
- Each color has anti-color charge: anti-red, anti-blue, and anti-green
- Gluons carry a color-anticolor pair (blue-antigreen) and thus interact with one another.

	Electromagnetic interactions	Strong interactions
Property	Charge	Color charge
Fermions	Charged particles	Quarks
Mediating bosons	Photons	Gluons
	Do not carry charge	Carry color charge
	Do not interact with themselves	Interact with themselves

Hadrons

- Hadrons consist of quarks:
  - Two quarks: mesons
  - Three quarks: baryons
- Hadrons are color charge neutral
  - Two quarks system = quark (color) + quark (anticolor) e.g. red + antired
  - Three quarks system: a quark carries one each of red, blue, and green colors
  - Zero net color leads to attraction

Hadrons

TABLE 12.2 Commonly produced hadrons

Baryons	Mass (MeV/c^2)	Spin	Strangeness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
p (uud)	938	$\frac{1}{2}$	0	$\frac{1}{2}, +\frac{1}{2}$	$>10^{32}$ yr
n (udd)	940	$\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	889 s
Σ^+ (uus)	1189	$\frac{1}{2}$	−1	1, +1	8.0×10^{-11} s
Σ^0 (uds)	1193	$\frac{1}{2}$	−1	1, 0	7.4×10^{-20} s
Λ^0 (uds)	1116	$\frac{1}{2}$	−1	0, 0	2.6×10^{-10} s
Σ^- (dds)	1197	$\frac{1}{2}$	−1	1, −1	1.5×10^{-10} s
Ξ^0 (uss)	1315	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	2.9×10^{-10} s
Ξ^- (dss)	1321	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	1.6×10^{-10} s
Δ^{++} (uuu)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{3}{2}$	120 MeV
Δ^+ (uud)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{1}{2}$	120 MeV
Δ^0 (udd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{1}{2}$	120 MeV
Δ^- (ddd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{3}{2}$	120 MeV
Σ^{*+} (uus)	1383	$\frac{3}{2}$	−1	1, +1	~40 MeV
Σ^{*0} (uds)	1384	$\frac{3}{2}$	−1	1, 0	~40 MeV
Σ^{*-} (dds)	1387	$\frac{3}{2}$	−1	1, −1	~40 MeV
Ξ^{*0} (uss)	1532	$\frac{3}{2}$	−2	$\frac{1}{2}, +\frac{1}{2}$	~10 MeV
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Ω^- (sss)	1672	$\frac{3}{2}$	−3	0, 0	8.2×10^{-11} s

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$K^+(u\bar{s})$	494	0	+1	$\frac{1}{2}, +\frac{1}{2}$	1.2×10^{-8} s
$K^0_S(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	8.9×10^{-11} s
$K^0_L(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	5.2×10^{-8} s
$K^-(s\bar{u})$	494	0	−1	$\frac{1}{2}, -\frac{1}{2}$	1.2×10^{-8} s
$\rho^+(u\bar{d})$	769	1	0	1, +1	151 MeV
$\rho^0(u\bar{u} + d\bar{d})$	769	1	0	1, 0	151 MeV
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$K^{*+}(u\bar{s})$	892	1	+1	$\frac{1}{2}, +\frac{1}{2}$	50 MeV
$K^{*0}(d\bar{s})$	896	1	+1	$\frac{1}{2}, -\frac{1}{2}$	51 MeV
$\overline{K^{*0}}(s\bar{d})$	896	1	−1	$\frac{1}{2}, +\frac{1}{2}$	51 MeV
$K^{*-}(s\bar{u})$	892	1	−1	$\frac{1}{2}, -\frac{1}{2}$	50 MeV
Heavy mesons—containing quarks beyond the strange					
$J/\psi\ (c\bar{c})$	3100	1	0	0, 0	87 keV
$\Upsilon\ (b\bar{b})$	9460	1	0	0, 0	~50 keV

50 MeV corresponds to a lifetime of 10^{-23} second

Hadrons

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$\rho^+(u\bar{d})$	769	1	0	1, +1	151 MeV

Quarks

Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
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Construct charge
Color charge
Compare mass

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Construct charge
Color charge
Compare mass

Hadron: intrinsic properties

- Spin:
  - Three quarks → ½ or 3/2
  - Two quarks → 0 or 1
- Isospin(I):
  - Up and down quarks' I = ½
  - Strange quark's I = 0
  - Differentiate Σ^0 and Λ^0
- Strangeness (S):
  - The number of strange quarks
  - When having one strange quark, S=-1, two S=-2
  - When having one antistrange quakr, S=+1

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$J/\psi\ (c\bar{c})$	3100	1	0	0, 0	87 keV
$\Upsilon\ (b\bar{b})$	9460	1	0	0, 0	~50 keV

50 MeV corresponds to a lifetime of 10^{-23} second

Hadron: intrinsic properties

- Spin:
  - Three quarks → ½ or 3/2
  - Two quarks → 0 or 1
- Isospin(I):
  - Up and down quarks' I = ½
  - Strange quark's I = 0
  - Differentiate Σ^0 and Λ^0
- Strangeness (S):
  - The number of strange quarks
  - When having one strange quark, S=-1, two S=-2
  - When having one antistrange quark, S=+1

Hadrons

TABLE 12.2 Commonly produced hadrons

Baryons	Mass (MeV/c^2)	Spin	Strangeness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
p (uud)	938	$\frac{1}{2}$	0	$\frac{1}{2}, +\frac{1}{2}$	$>10^{32}$ yr
n (udd)	940	$\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	889 s
Σ^+ (uus)	1189	$\frac{1}{2}$	−1	1, +1	8.0×10^{-11} s
Σ^0 (uds)	1193	$\frac{1}{2}$	−1	1, 0	7.4×10^{-20} s
Λ^0 (uds)	1116	$\frac{1}{2}$	−1	0, 0	2.6×10^{-10} s
Σ^- (dds)	1197	$\frac{1}{2}$	−1	1, −1	1.5×10^{-10} s
Ξ^0 (uss)	1315	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	2.9×10^{-10} s
Ξ^- (dss)	1321	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	1.6×10^{-10} s
Δ^{++} (uuu)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{3}{2}$	120 MeV
Δ^+ (uud)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{1}{2}$	120 MeV
Δ^0 (udd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{1}{2}$	120 MeV
Δ^- (ddd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{3}{2}$	120 MeV
Σ^{*+} (uus)	1383	$\frac{3}{2}$	−1	1, +1	~40 MeV
Σ^{*0} (uds)	1384	$\frac{3}{2}$	−1	1, 0	~40 MeV
Σ^{*-} (dds)	1387	$\frac{3}{2}$	−1	1, −1	~40 MeV
Ξ^{*0} (uss)	1532	$\frac{3}{2}$	−2	$\frac{1}{2}, +\frac{1}{2}$	~10 MeV
Ξ^{*-} (dss)	1535	$\frac{3}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	~10 MeV
Ω^- (sss)	1672	$\frac{3}{2}$	−3	0, 0	8.2×10^{-11} s

Mesons	Mass (MeV/c^2)	Spin	Strangeness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
$\pi^+(u\bar{d})$	140	0	0	1, +1	2.6×10^{-8} s
$\pi^0(u\bar{u} + d\bar{d})$	135	0	0	1, 0	8.4×10^{-17} s
$\pi^-(d\bar{u})$	140	0	0	1, −1	2.6×10^{-8} s
$K^+(u\bar{s})$	494	0	+1	$\frac{1}{2}, +\frac{1}{2}$	1.2×10^{-8} s
$K^0_S(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	8.9×10^{-11} s
$K^0_L(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	5.2×10^{-8} s
$K^-(s\bar{u})$	494	0	−1	$\frac{1}{2}, -\frac{1}{2}$	1.2×10^{-8} s
$\rho^+(u\bar{d})$	769	1	0	1, +1	151 MeV
$\rho^0(u\bar{u} + d\bar{d})$	769	1	0	1, 0	151 MeV
$\rho^-(d\bar{u})$	769	1	0	1, −1	151 MeV
$K^{*+}(u\bar{s})$	892	1	+1	$\frac{1}{2}, +\frac{1}{2}$	50 MeV
$K^{*0}(d\bar{s})$	896	1	+1	$\frac{1}{2}, -\frac{1}{2}$	51 MeV
$\overline{K^{*0}}(s\bar{d})$	896	1	−1	$\frac{1}{2}, +\frac{1}{2}$	51 MeV
$K^{*-}(s\bar{u})$	892	1	−1	$\frac{1}{2}, -\frac{1}{2}$	50 MeV
Heavy mesons—containing quarks beyond the strange					
$J/\psi\ (c\bar{c})$	3100	1	0	0, 0	87 keV
$\Upsilon\ (b\bar{b})$	9460	1	0	0, 0	~50 keV

50 MeV corresponds to a lifetime of 10^{-23} second

Residual strong force

- Holds two nucleons together in the nucleus
- Between uud protons and udd neutrons by the exchange of a particle called pion.

Electroweak force

- Particles should have charge or weak charge
- Quarks and leptons can engage in this force
-Leptons do not have color charges and have antiparticles.
-Leptons have antiparticles
- Electron, muon, and tauon are very much alike except their mass.

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Mediating Bosons:
-electromagnetic part of the force: photons, massless and spin 1
-weak part of the force: heavy bosons W^+, W^-, Z^0 with charge, spin 1

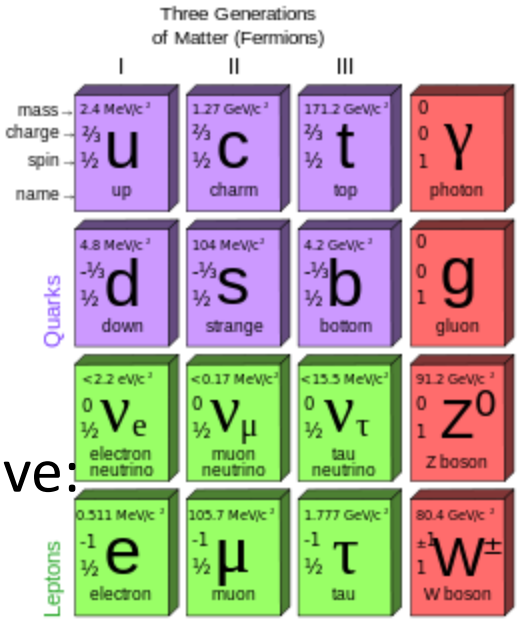
Why four different field quantas?

- Spontaneously broken symmetry occurs at low particle energies.
- At very high energies, the intrinsic mass of a particle becomes irrelevant and the behaviors of the mediating particles converge.
- Neutrinos are not charged and thus do not engage in electromagnetic interactions.
- All leptons have weak charge and engage in weak interactions.
- Electromagnetic force > weak force because whether the mediating particles have mass or not.
  - Since photons do not have mass, the electromagnetic force is stronger than the weak force which is short-ranged.

Elementary particles

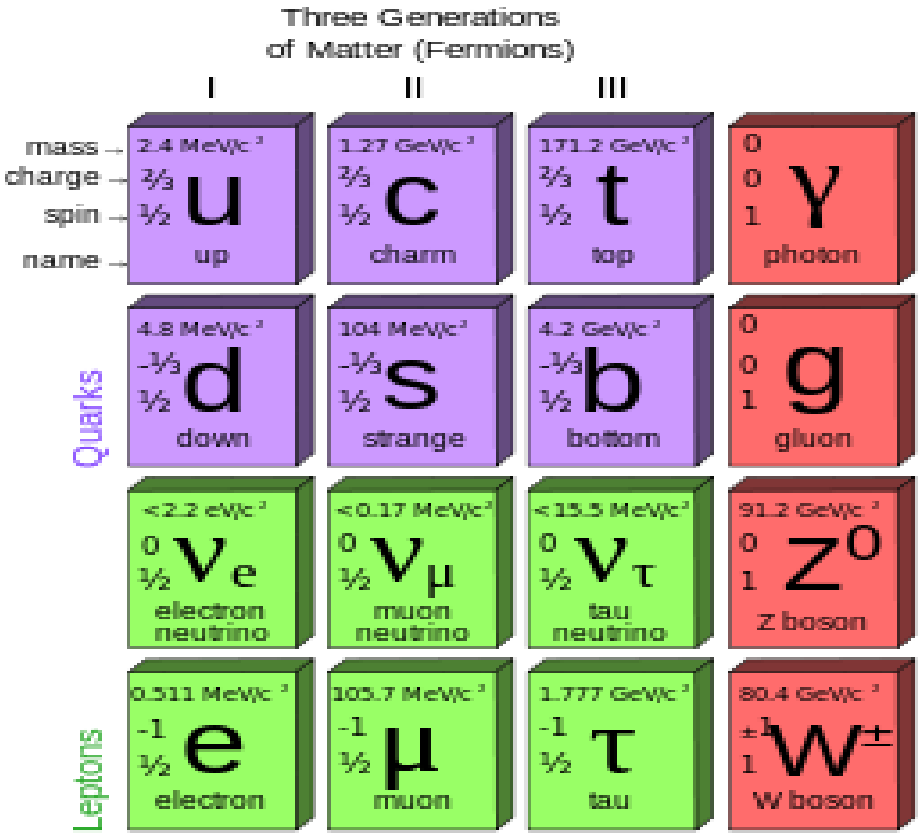
Three classes of particles:

- Six quarks → strong force
- Six leptons → electroweak force
- Four mediating particles (bosons) called field quanta
  - → Graviton: gravitational force
  - → Photon: electromagnetic force
  - → W^+, W^-, Z^0: weak force
  - → Gluon: strong force between quarks
  - → Pion: residual strong force between nucleons



- Particles experiencing forces (fermions) should have:
  - Mass/energy for gravitational force
  - Charge/weak charge for electroweak force
  - Color charge for strong force

Standard Model



Charge
Spin
Mass

Conservation rules

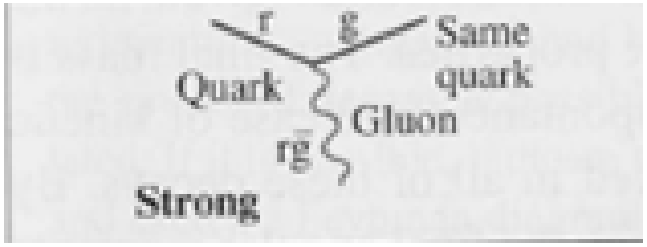
TABLE 12.4 Some conservation rules

Conserved? / Interaction	Momentum, Energy, Angular Momentum, Charge, Color	Baryon Number (B)	Lepton Numbers* (L_e, L_μ, L_τ)	Strangeness	Parity (P)	Charge Conjugation (C)	Time Reversal (T)
Strong	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electromagnetic	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak	Yes	Yes	Yes	No	No	No	No

* Recent evidence indicates some exceptions.

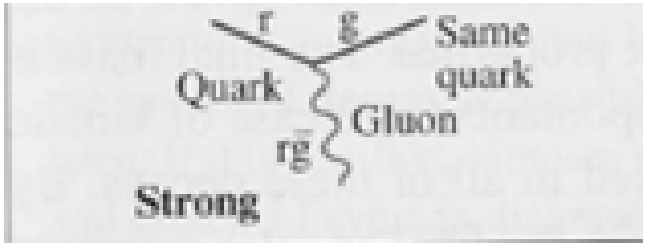
Energy: decay products' energy cannot be higher than initial particle's energy
Spin
Charge
Baryon Number: +1 for a baryon, -1 for an antibaryon, 0 for nonbaryons.
Lepton Number: Separately done for electron, muon, and tauon. 1 for each electron and electron neutrino and -1 for each corresponding antiparticle
Strangeness: +1 for one antistrange quark, -1 for one strange quark

Feynman Diagram

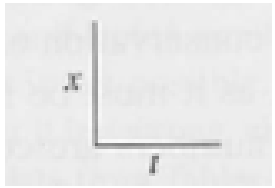


Vertex
Incoming and outgoing lines
Wavy lines
Time representation

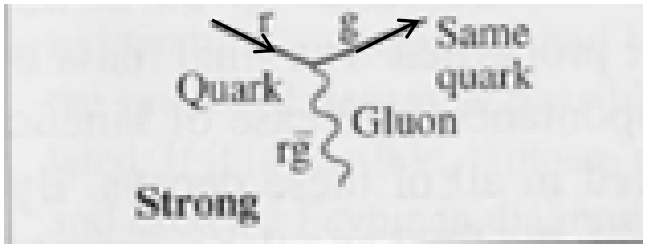
Feynman Diagram



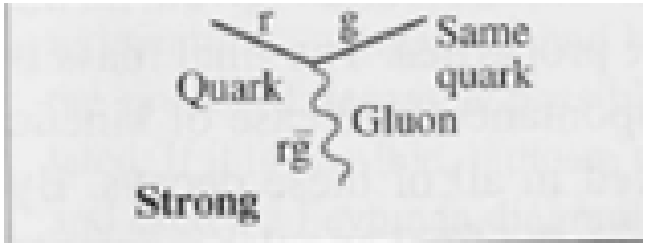
Vertex
Incoming and outgoing lines
Wavy lines
Time representation

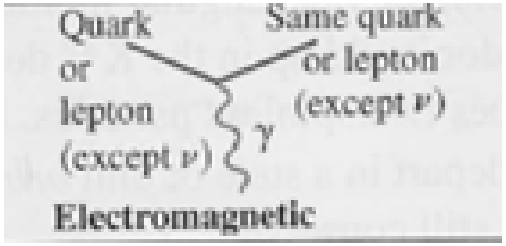


Or use arrows



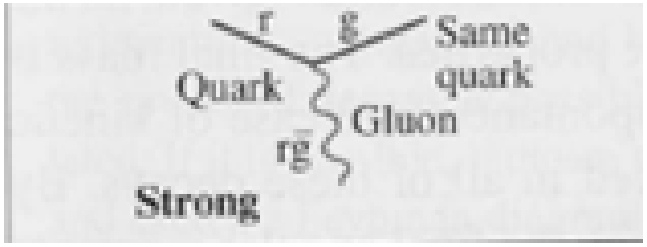
Feynman Diagram

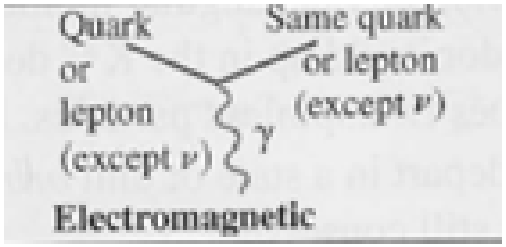




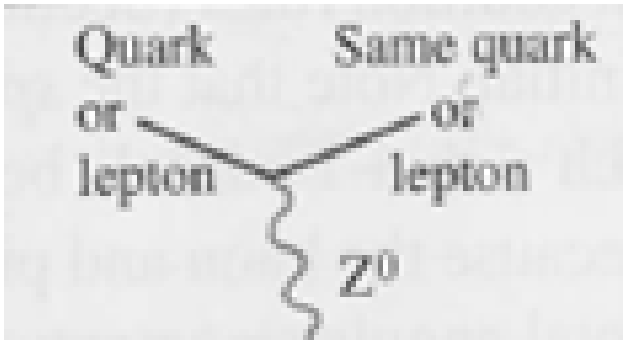
Practice:
Weak force mediated by Z^0 from quark to quark

Feynman Diagram





Practice:
Weak force mediated by Z^0 from quark to quark



Weak Interactions

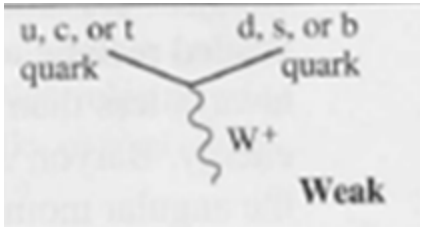
Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Weak force mediated by W^+ from quark to quark



Weak Interactions

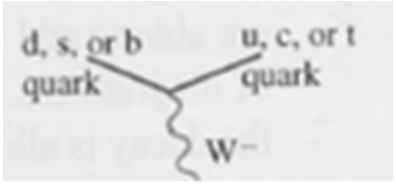
Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Weak force mediated by W^- from quark to quark



Weak Interactions

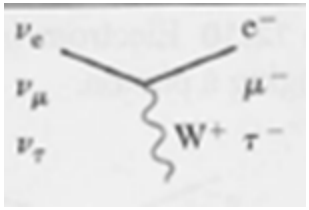
Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Weak force mediated by W^+ from neutrino to electron



Weak Interactions

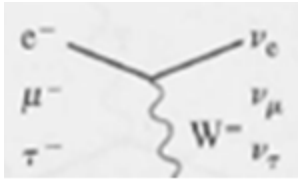
Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Weak force mediated by W^- from electron to neutrino



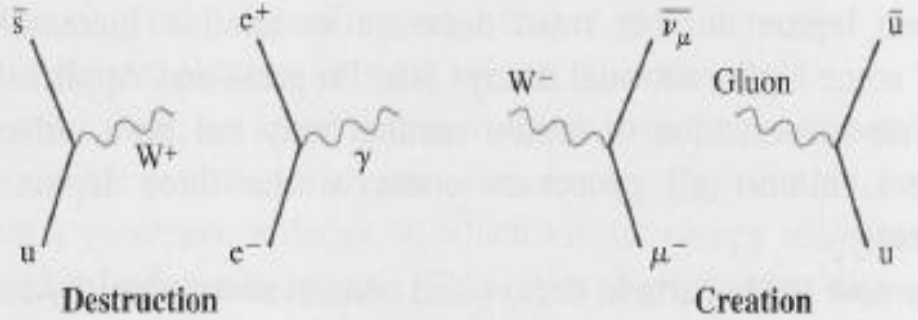
Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

Leptons
Participants in gravitation and electroweak

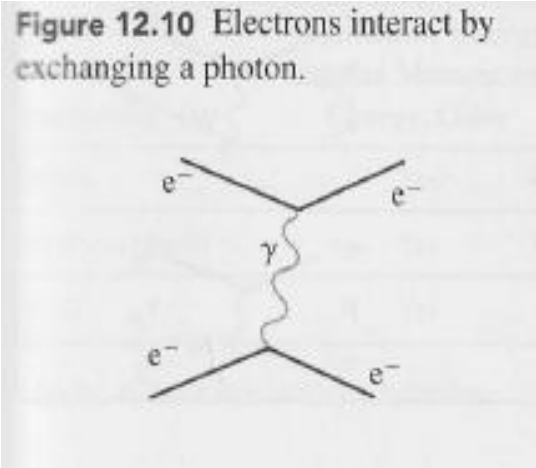
	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Figure 12.9 Representative destruction and creation vertices.



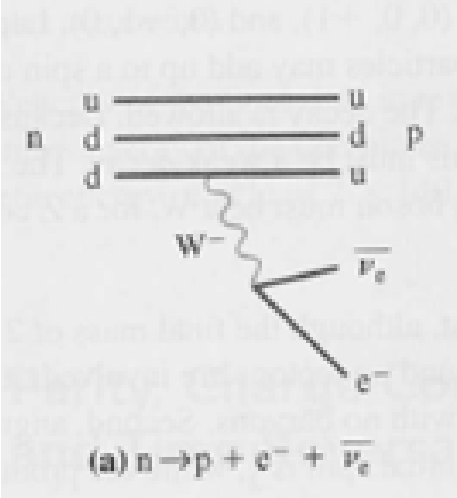
Charge conserved?
Spin conserved?
Which one needs color charge conservation?

What is shown?



Possible?

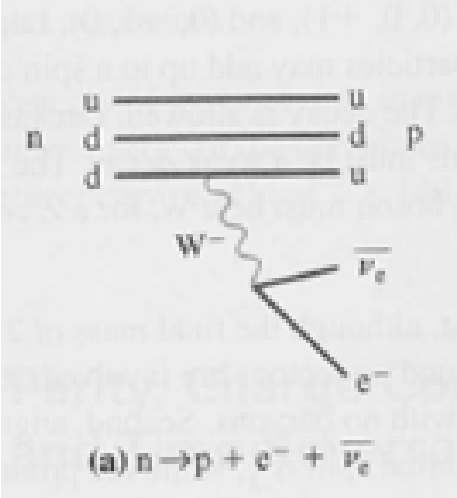
Mass=
Spin=
Strangeness=
Baryon number=
Lepton number=



Mass=
Spin=
Strangeness=
Baryon number=
Lepton number=

Decay Possible?

Mass=940
Spin=1/2
Strangeness=0
Baryon number=1
Lepton number (e)=0



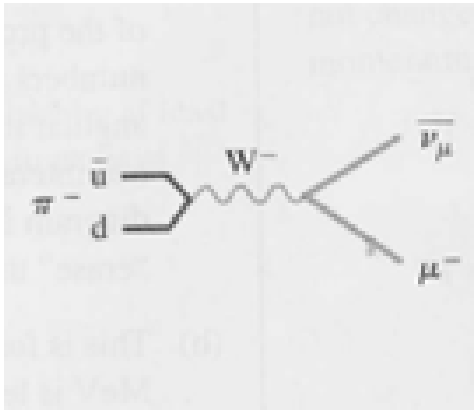
Mass=938
Spin=1/2
Strangeness=0
Baryon number=1
Lepton number=0

Mass=0
Spin=1/2
Strangeness=0
Baryon number=0
Lepton number=-1

Mass=0.51
Spin=1/2
Strangeness=0
Baryon number=0
Lepton number=1

Possible?

Mass=
Spin=
Strangeness=
Baryon number=
Lepton number (μ)=



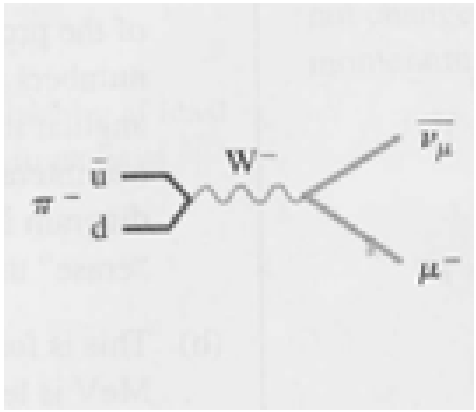
(b) $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$

Mass=
Spin=
Strangeness=
Baryon number=
Lepton number (μ)=

Mass=
Spin=
Strangeness=
Baryon number=
Lepton number (μ)=

Possible?

Mass=140
Spin=0
Strangeness=0
Baryon number=0
Lepton number (μ)=0



(b) $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$

Mass=0
Spin=1/2
Strangeness=0
Baryon number=0
Lepton number (μ)=-1

Mass=106
Spin=1/2
Strangeness=0
Baryon number=0
Lepton number (μ)=1

Possible?

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

Possible?

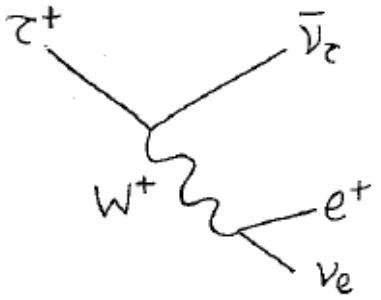
$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

	Before	After		
	τ^+	e^+	ν_e	$\bar{\nu}_\tau$
Mass	1780			
Charge	+1			
Spin	1/2			
Strangeness	0			
Baryon Number	0			
Lepton Number- τ	-1			
Lepton Number-e	0			

Possible?

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

	Before	After		
	τ^+	e^+	ν_e	$\bar{\nu}_\tau$
Mass	1780	.511	0	0
Charge	+1	+1	0	0
Spin	1/2	1/2	1/2	1/2
Strangeness	0	0	0	0
Baryon Number	0	0	0	0
Lepton Number- τ	-1	0	0	-1
Lepton Number-e	0	-1	+1	0



Possible?

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

Possible?

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

	Before	After		
	$\bar{n}$	p	e^{-}	$\bar{\nu}_e$
Mass	940	938	.511	0
Charge	0	1	-1	0
Spin	1/2	1/2	1/2	1/2
Strangeness	0	0	0	0
Baryon Number	-1	1	0	0
Lepton Number-e	0	0	1	-1

Possible?

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

Possible?

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

	Before	After	
	Ξ^-	Λ^0	π^-
Mass	1321	1116	140
Charge	-1	0	-1
Spin	1/2	1/2	0
Strangeness	(dss) -2	(uds) -1	0
Baryon Number	1	1	0

Possible?

$$\Xi^- \rightarrow \Lambda^0 + \pi^-$$

	Before	After	
	Ξ^-	Λ^0	π^-
Mass	1321	1116	140
Charge	-1	0	-1
Spin	1/2	1/2	0
Strangeness	(dss) -2	(uds) -1	0
Baryon Number	1	1	0