PH102, 2013W, Lecture Notes: March 12, Tues, Lecture 19

Fundamental forces

The unified theory is intended to describe all interactions as different aspects of a single fundamental interaction. Why we believe this might be the case:

- Fundamental particles experiencing a force are fermions and mediating particles for the force are bosons.
- For a fermion to engage in a force, the fermion has a property associated with the force:
    - Mass/energy for gravitational force
    - Charge or weak charge for electroweak force
    - Color charge for strong force

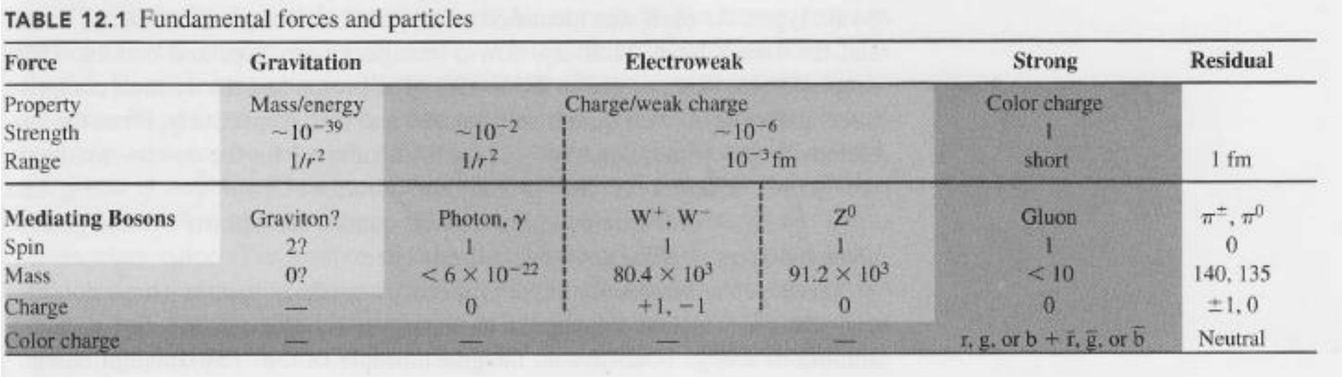
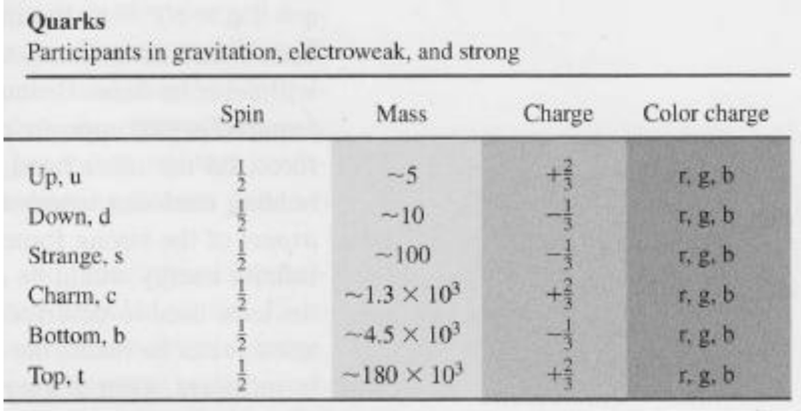


TABLE 12.1 Fundamental forces and particles

Force	Gravitation	Electroweak			Strong	Residual
Property	Mass/energy	Charge/weak charge			Color charge	
Strength	~10^{-39}	~10^{-2}	~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	$\pi^\pm$, π^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	±1, 0
Color charge	—	—	—	—	r, g, or b + $\bar{r}$, $\bar{g}$, or $\bar{b}$	Neutral

Strong Force

- Protons and neutrons that make up a nucleus are not fundamental particles. They are made up of quarks that are bound by the strong force.
- Six types of quarks exist: up, down, strange, charm, bottom and top. See the Table on the right.
- Quarks have a spin of ½, have mass, have either +2/3 or -1/3 charge.
- Hadrons are particles made up of quarks. For example,
    - Proton (uud)=spin ½ and charge +1 $\left(=\frac{2}{3}+\frac{2}{3}-\frac{1}{3}\right)$
    - Neutron (udd)=spin ½ and charge 0 $(=\frac{2}{3}-\frac{1}{3}-\frac{1}{3})$
- Quarks are not separable, making a fundamental charge of $e = 1.6 \text{ x } 10^{-19}$C safe.
- The internal structure of a nucleon (thus quark existence) is shown by deep inelastic scattering experiments where high energy electrons (greater than 20 GeV and a scattering length of 0.1 fm, smaller than the size of a nucleus).
- Gluons are the mediating boson of the strong force and have spin-1 and massless.



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	$\frac{1}{2}$	~1.3×10^3	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	~4.5×10^3	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	~180×10^3	$+\frac{2}{3}$	r, g, b

- The property quarks need to have to carry the strong force is color (charge).
    - Three color charge types: red, blue, and green.
    - Each color has anti-color charge: antired, antiblue, and antigreen
    - Only quarks possess charge color so only quarks carry the strong force.
    - Gluons carry a color-anticolor pair of color charge (e.g. blue-antigreen) and thus interact with one another. This makes the strong force different from electroweak force where photons do not carry charge and do not interact with one another.
    - Hadrons are color charge neutral, but there are attractions in a color charge neutral system, similarly to that atoms are charge neutral but there is attraction in a charge neutral system.
    - Hadrons are color charge neutral
        - Three quarks that carry one of each color (blue+red+green=neutral)
        - Quark (color)-antiquark (anticolor) pair (red +antired=neutral)
- Gluons are not separable and thus colors are not separable
- The study of strong interactions is called quantum chromodynamics (QCD).
- Though a nucleon consists of three quarks, the nucleon mass cannot be just consisting of three quark masses. The nucleon mass should also account for the sizable cloud of energetic gluons and virtual quark-antiquark pairs constantly undergoing creation and annihilation. This cloud consists of the majority of the nucleon mass.

Hadrons consist of quarks. There are six quarks and corresponding six antiquarks. Commonly produced hadrons are shown in Table 12.2.

- Baryons consist of three quarks: examples-proton and neutron
    - Most baryons are heavier than proton and neutron and short lived. For very short-lived Baryons energy width is used instead of time. An energy width of 50 MeV corresponds with a lifetime of 10^{-23} second.
- Mesons consist of two quarks: example: π mesons
    - $\pi^+ = u\bar{d}$, charge 2/3+1/3=+1; color should be red-antired or blue-antiblue or green-antigreen
    - $\pi^0 = u\bar{u} + d\bar{d}$, charge = 0 since a mixture of 2/3 and -2/3 as well as 1/3 and -1/3
    - $\pi^- = d\bar{u}$, this is antiparticle of π^+, thus opposite charge -

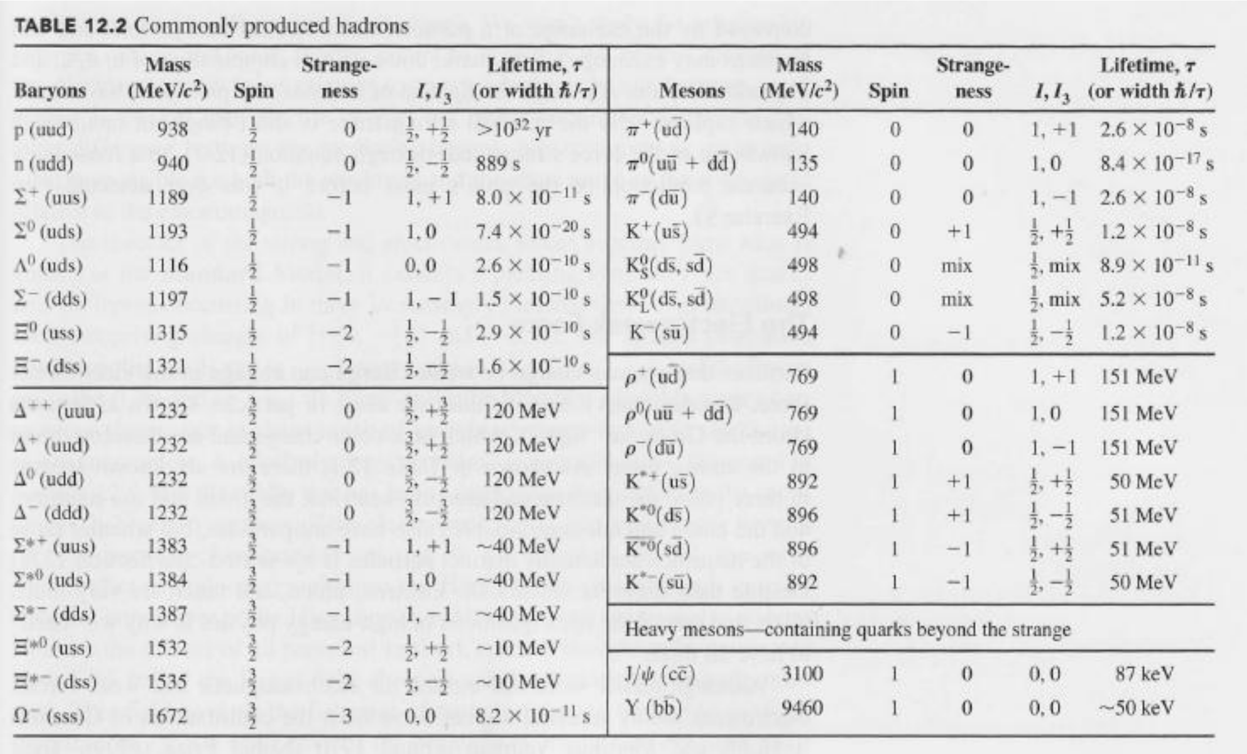


TABLE 12.2 Commonly produced hadrons

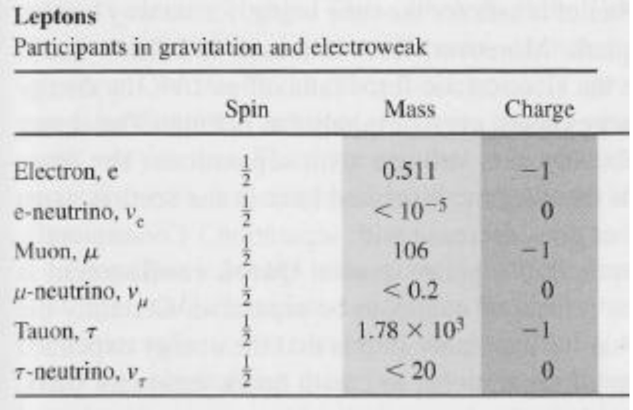
Baryons	Mass (MeV/c^2)	Spin	Strange-ness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
p (uud)	938	$\frac{1}{2}$	0	$\frac{1}{2}, +\frac{1}{2}$	$>10^{32}$ yr
n (udd)	940	$\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	889 s
Σ^+ (uus)	1189	$\frac{1}{2}$	−1	1, +1	8.0×10^{-11} s
Σ^0 (uds)	1193	$\frac{1}{2}$	−1	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	Strange-ness	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

- Hadrons' Intrinsic Properties
  - Spin:
    - Since Baryons consist of three quarks, their spins can be either 3/2 or ½.
    - Since Mesons consist of two quarks, their spins can be either 1 or 0.
  - Isospin, (I, I_z): this is not an angular momentum, but treated similarly in terms of mathematical treatment.
    - Up and down quarks have I=1/2 and strange quark has I=0.
    - Isospin can differentiate $\Sigma^0$and Λ^0 where both has the same quark makeup uds and the same spin of ½. But the isospin of ud quarks are aligned for Σ^0 and antialigned for Λ^0, giving I=1 for the former and I=0 for the latter.
  - Strangeness arises with the strange quark. One strange quark gives -1; two -2, no strange quark 0, one anti strange quark +1, etc.
- Residual strong force
  - This force holds two nucleons together in the nucleus.
  - This force can be conveyed between uud protons and udd neutrons by the exchange of a particle called pion which can consist of two of u, d, $\bar{u}$, and $\bar{d}$.

Electroweak Force

- Particles that possess charge or weak charge can engage in the electroweak force.
- Quarks and leptons can be engaged in the electroweak force.

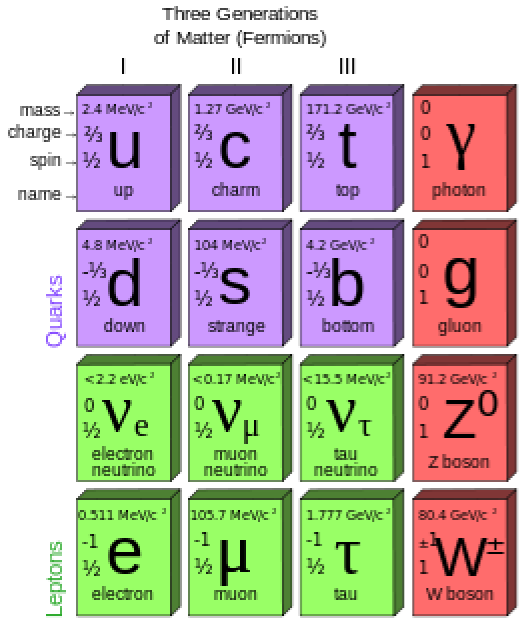


Leptons
Participants in gravitation and electroweak

	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

- Leptons do not have color charges and there are six leptons shown in the Table on the right.
- All six leptons have antiparticles, but whether antiparticles of the neutrinos are distinct is not determined.
- Electron, muon, and tauon are very much alike except their masses.
- The electroweak force is conveyed by the exchange of the four mediating bosons:
  - Massless photon for the electromagnetic part of the force
  - Heavy bosons, W^+, W^-, Z^0, for the weak part of the force
- Why we have four different types of field quanta for the same field?
  - 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. But all leptons have weak charge and engage in weak interactions. The reason why the electromagnetic force is larger than the weak force is due to 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.

The Standard Model combines the electroweak force and the strong force to show the symmetry among six leptons, six quarks, and 4 mediating bosons. See the Figure below. The particles are organized by mass from light to heavy (left to right) and by charge (2/3. -1/3, 0, -1)e. The electroweak force's spontaneously broken symmetry provides a problem to the Standard Model. A solution might be related to Higgs Boson, its discovery is one of the most important goals of the current elementary particle physics.



Gravitational Force

- Gravitational force applies to all particles with mass or any other form of energy.

- The force is attractive.
- No quantum aspects of the force have been observed possibly due to its weakness.
- In theory, the mediating boson should have a spin of 2 and massless (because it is long range).

Many particles produced at accelerators are unstable (except proton) and thus decay very quickly. Basically, the study of elementary particles is the study of decay during strong, electromagnetic, and weak interactions.

Conservation Rules: All particle decay processes should not violate conservation rules. We can use conservation rules listed in Table 12.4 to determine whether or not certain decay processes are possible.

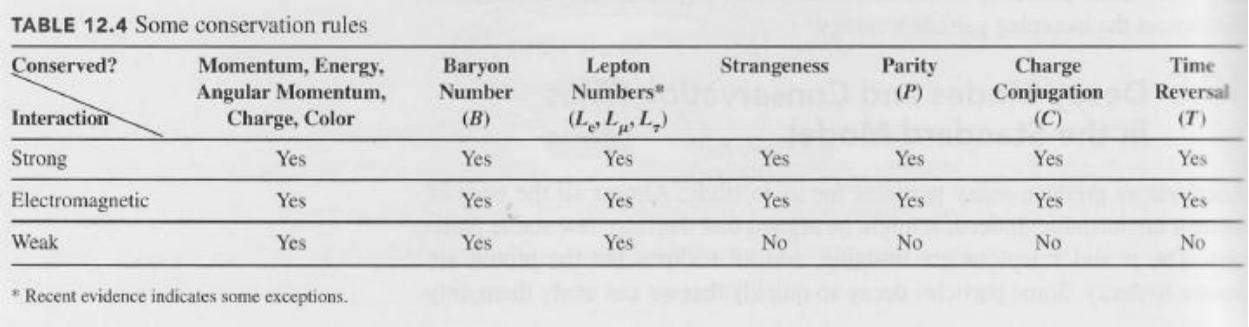


TABLE 12.4 Some conservation rules

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

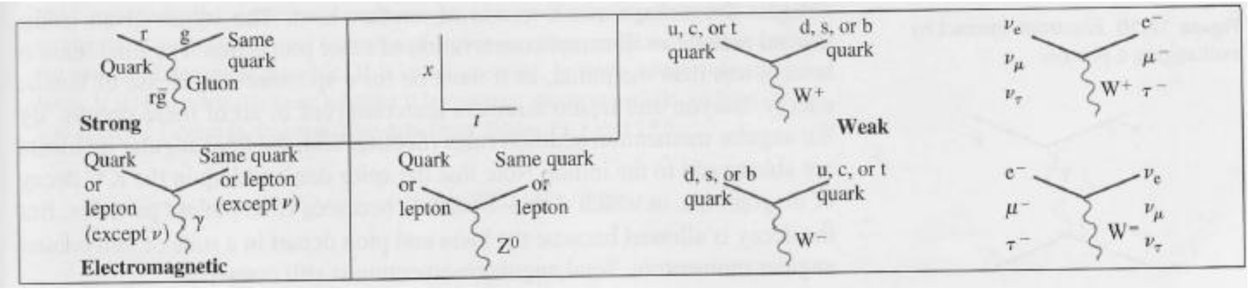
* Recent evidence indicates some exceptions.

- Energy and momentum conservation indicates all massive particles should decay to the lighter particles. If product particles have larger masses than initial particles, then initial particles should have enough kinetic energies to make the process possible.
- Note that these conservation rules are based on observations and found to be not yet violated.
- Baryon number is conserved. Assign B as +1 for a baryon, -1 for an antibaryon, 0 for nonbaryons.
- There are three lepton numbers. Each lepton number is conserved.
    - Electron lepton number:
      $L_e = 1 \text{ for electron and electron neutrino}, -1 \text{ for correponding antiparticles}$
    - Muon lepton number:
      $L_\mu = 1 \text{ for muon and muon neutrino}, -1 \text{ for correponding antiparticles}$
    - Tau lepton number:
      $L_\tau = 1 \text{ for tau and tau neutrino}, -1 \text{ for correponding antiparticles}$
      Recent studies suggest that conservation of lepton number may not be universal.
- Strangeness is conserved Strangeness arises with the strange quark. One strange quark gives -1; two -2, no strange quark 0, one anti strange quark +1, etc.
- Parity Inversion (P) changes signs of all three spatial coordinates: (x, y, z) → (-x, -y, -z). The weak force is not symmetric under parity inversion.
- Charge conjugation (C) replaces all particles with their antiparticles. The weak force is not symmetric under charge conjugation

- Time reversal (T) replaces t with –t. The weak force is not symmetric under time reversal.
- CPT theorem: under the combined CPT operations, all interactions are invariant.

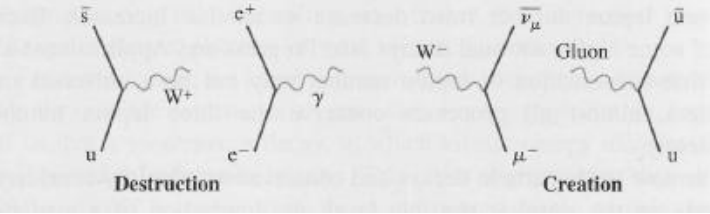
Feynman Diagrams

- Vertex represents the interaction point
- Lines that enter and leave the diagram represent observable particles.
- Wavy lines represent mediating bosons.
- Time can be shown using arrows or as indicated in the diagram.



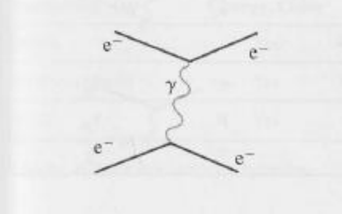
- Feynman diagrams are shown above for strong, electromagnetic and weak forces.
  - Strong force works between quarks and mediating particle is gluon. The color should be conserved. A quark in the strong force can change color if a gluon carries a color-anticolor pair.
  - Electromagnetic force affects quarks and leptons with charge. The mediating boson is photon.
  - Weak interactions involve all quarks and leptons and the mediating bosons are W^+, W^- and Z^0.
    - W^+ carries +1 thus changes the charge by -1 (u→ d; c→s; t→ b or neutrino to the other member of its lepton pair)
    - W^- carries -1 thus changes the charge by +1 (d→ u; s→ t; b→ t or leptons to the other member of its neutrino pair)
    - Z^0 carries no charge, thus does not change the particle.
- Particle annihilation and production can be shown in Figure 12.9

Figure 12.9 Representative destruction and creation vertices.

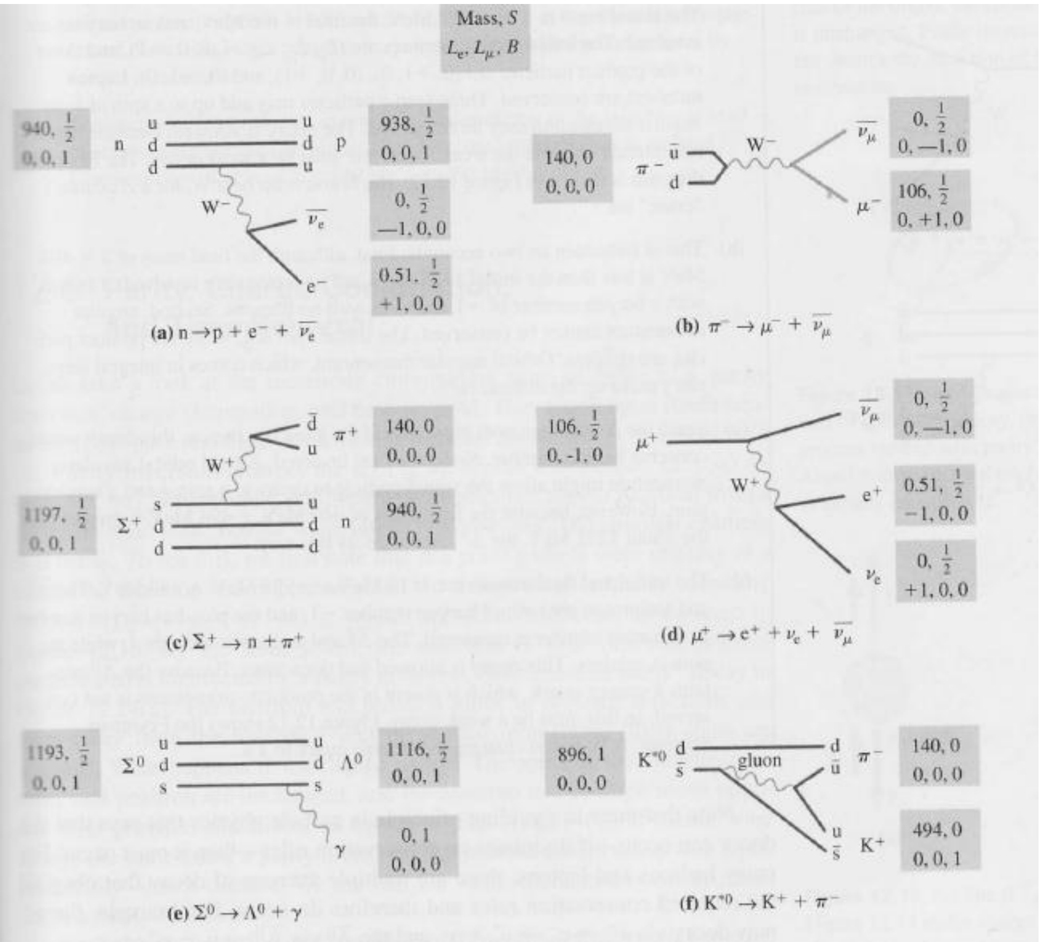


- We can put two vertices together to describe the whole process. For example, Figure 12.10 shows one electron emitting a photon and the other electron receiving the photon.

Figure 12.10 Electrons interact by exchanging a photon.



Examples of spontaneous decays using Feynman diagrams:
Note that conservation rules should be satisfied for all decays.



- Final mass is always smaller than initial mass
- Final product particles' spins should add up to the spin of an initial particle.
- Lepton number is conserved
- Baryon number is conserved
- Strangeness number is not conserved in (c) weak interaction.
- In (f), spin is not conserved. But the total angular momentum is because pion and kaon depart with the angular momentum that matches the spin angular momentum.

Low energy symmetry breaking in weak interactions

- Parity inversion does not change the direction of angular momentum. See Figure 12.14.
- Let's consider Parity inversion of β^+decay:

$$ {}^{A}_{Z}X(parent) \rightarrow {}_{Z-1}^{A}Y(daughter) + {}^{\mathbf{0}}_{+\mathbf{1}}\boldsymbol{\beta}^{+} + \boldsymbol{\nu} $$

Figure 12.14(a) shows that a parent nucleus emits a positron and neutrino. The direction of positron and that of neutrino

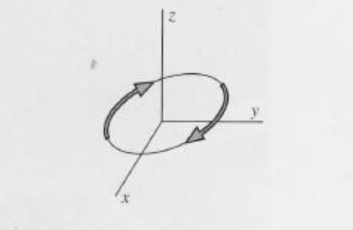
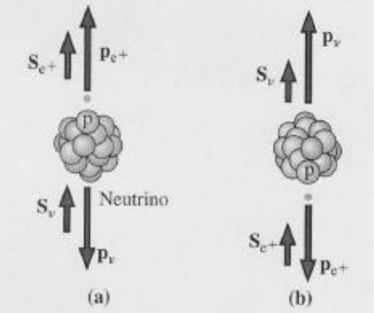


Figure 12.14 (a) A nucleus losing 1 unit of spin in β^+ decay. (b) The process viewed with parity reversed. Angular momenta are unchanged, but velocities are opposite.

are opposite. When parity inversion is applied, spins do not change for the positron and the neutrino, but the directions of the positron and the neutrino change from 12.14 (a) and the spatial location of the proton in the nucleus changes as well, shown in Figure 12.14(b). In nature, 12.14(b) is unlikely to be observed, thus making weak interactions have broken symmetry in parity inversion.

- Charge conjugation is operated on Figure 12.14 (a) by changing all particles in 12.14(a) into antiparticles, creating Figure 12.15(a). We apply parity inversion on 12.15(a) to obtain 12.15(b). In nature, 12.15(a) is unlikely, but 12.15(b) is likely. This illustrates that weak interactions' symmetry is broken with C or P separately operated. However, when CP operation is applied, the symmetry still holds.



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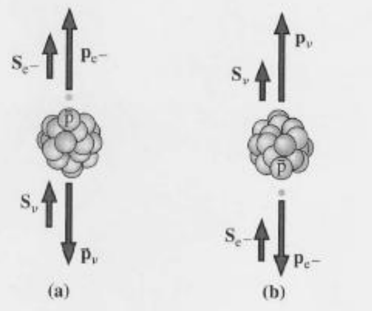

Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.