PH102, 2012W, Lecture Notes: March 14, Wed, Class 24

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

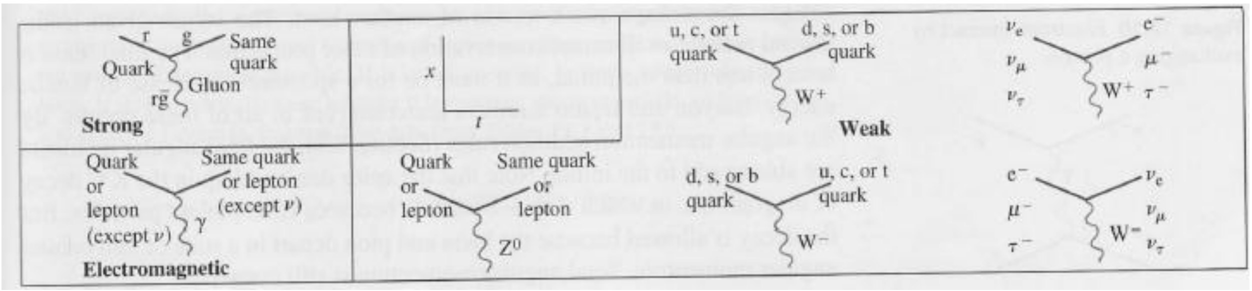
Conserved? / Interaction	Momentum, Energy, Angular Momentum, Charge, Color	Baryon Number (B)	Lepton Numbers* (L_e, L_μ, L_τ)	Strangeness	Parity (P)	Charge Conjugation (C)	Time Reversal (T)
Strong	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electromagnetic	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak	Yes	Yes	Yes	No	No	No	No

* 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:
    $L_e = 1$ for electron and electron neutrino, -1 for correponding antiparticles
  - Muon lepton number:
    $L_\mu = 1$ for muon and muon neutrino, -1 for correponding antiparticles
  - Tau lepton number:
    $L_\tau = 1$ for tau and tau neutrino, -1 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.

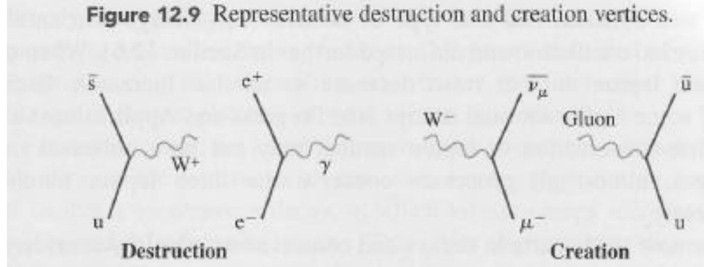
Feynman Diagrams

- 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.



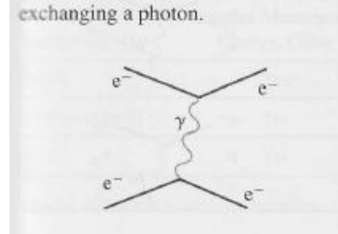
- Feynman diagrams are shown above for strong, electromagnetic and weak forces.
  - Strong force works between quarks and mediating particle is gluon. The color should be conserved. A quark in the strong force can change color if a gluon carries a color-anticolor pair.
  - Electromagnetic force affects 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.

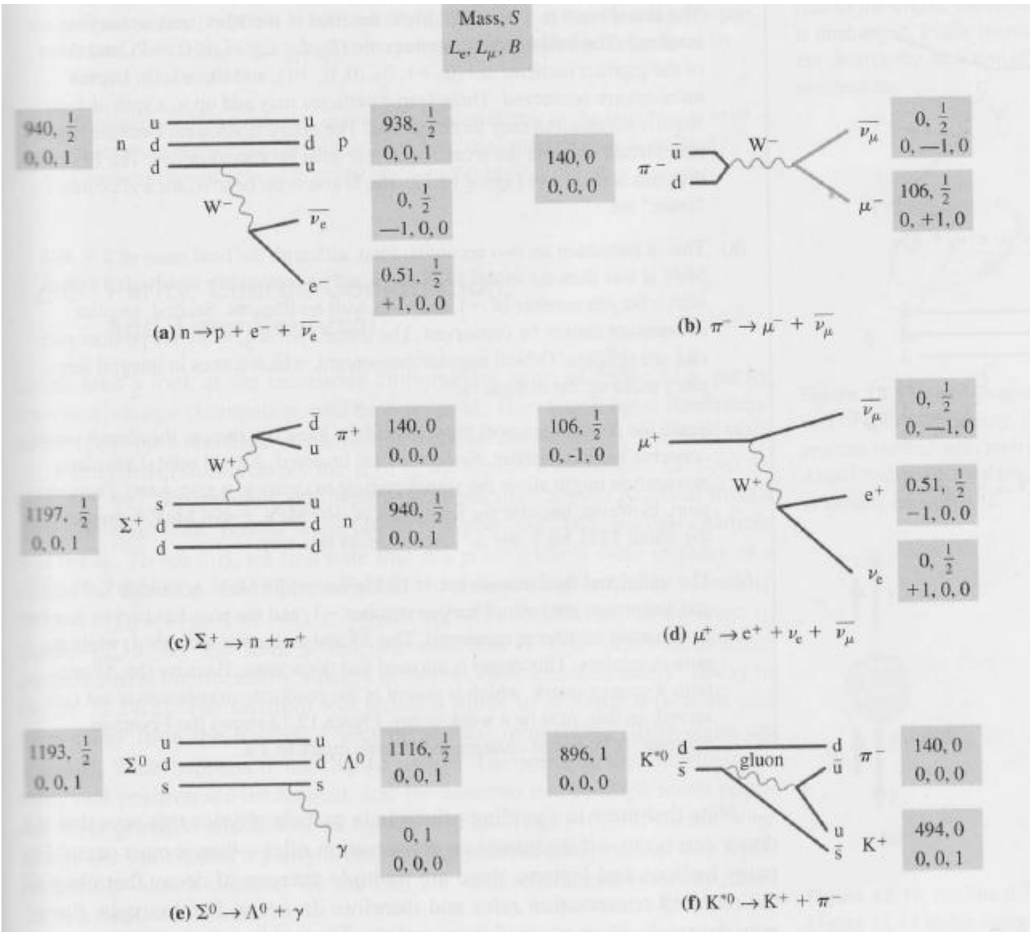


- We can put two vertices together to describe the whole process. For example, Figure 12.10 shows one electron emitting a photon and the other electron receiving the photon.

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:

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

Figure 12.14(a) shows that a parent nucleus emits a positron and neutrino. The direction of positron and that of neutrino are opposite. When parity inversion is applied, spins do not

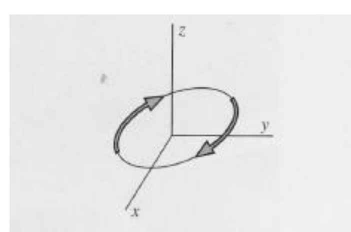


Figure 12.14 (a) A nucleus losing 1 unit of spin in β^+ decay. (b) The process viewed with parity reversed. Angular momenta are unchanged, but velocities are opposite.

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.

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.

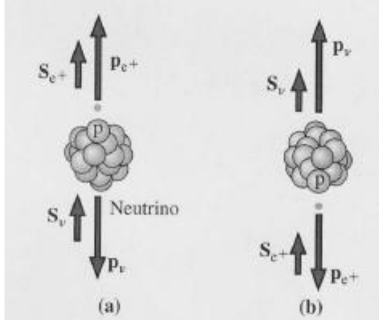
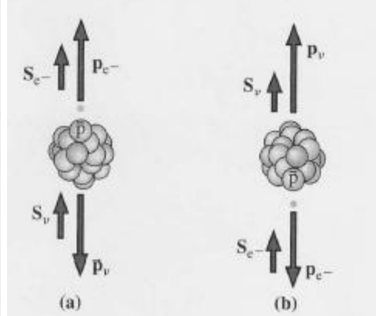


Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.



Symmetry operation and Conserved quantity

Symmetry operation	*Conserved quantity*
All interactions are independent of:	
Translation in space	Linear momentum **p**
Translation in time	Energy E
Rotation in space	Angular momentum **L**
Electromagnetic gauge transformation	Electric charge q
Lorentz transformation	Velocity of center of mass **V**
Interchange of identical particles	Type of statistical behavior
Inversion of space, time, and charge	Product of charge parity, space parity, and time parity CPT
?	Baryon number B
?	Lepton number L
?	Lepton number M
The strong and electromagnetic interactions only are independent of:	
Inversion of space	Parity P
Reflection of charge	Charge parity C, isotopic spin component I_3, and strangeness S
The strong interaction only is independent of:	
Charge	Isotopic spin I