Lecture 36 - The first microsecond

What's important:
- baryon asymmetry
- grand unified theories

Text: Carroll and Ostlie, Sec. 28.2

Baryon asymmetry

Let's recall two calculations that were performed in previous lectures for different purposes. The first is the number density of photons in today's universe at $T = 2.73$ K:

$$N_\gamma = 2.02 \times 10^7 (2.73)^2 = 4.0 \times 10^8 \text{ m}^{-3}. \qquad (36.1)$$

Second, the critical mass density for today's universe, as calculated in Lec. 5, is

$$\rho_{crit} = 9 \times 10^{-27} \text{ kg/m}^3 \qquad \text{(for } H = 71 \text{ km / s•Mpc)}$$

If we assumed (incorrectly) that most of this mass density is in the form of nucleons at 1.67×10^{-27} kg per nucleon, this corresponds to a number density of

$$n = 9 \times 10^{-27} / 1.67 \times 10^{-27} \sim 5 \text{ m}^{-3}. \qquad (36.2)$$

Comparing these two numbers, we see that the ratio of photons to baryons obeys

$$[\textit{photons / baryons}] > 10^8$$

where the "greater than" reflects the fact that the mass of the universe is not all baryonic. Both the visible matter estimates, and those from Big Bang nucleosynthesis in Lec. 35, place the baryon density at 2-5 % of the critical density, so a better estimate is (5% of 5 per m^3 = 0.25 m^{-3})

$$[\textit{photons / baryons}] \sim 10^9. \qquad (36.3)$$

Given that protons have a lifetime of at least 10^{31} years, this ratio has had the same value for much of the history of the universe; that is:

$$[\textit{baryon number density}] \sim R^{-3}$$
$$[\textit{photon number density}] \sim T^3 \sim R^{-3},$$

so the ratio is independent of the length scale factor R.

What about today's anti-baryons? Although baryons are found in small numbers in cosmic rays, their presence is consistent with production though high-energy collisions of normal matter. There is no visible evidence for the existence of a boundary between a universe of normal matter, and one of antimatter, where gamma rays of specific energies would be expected from matter-anti-matter annihilation. Of course, it is always possible that our visible region of the universe is matter, and another region more than 10 billion light years away is antimatter (perhaps in an inflationary scenario).

At the very high temperatures existing in the early universe (say $T > 10^{12}$ K or $k_B T > 86$ MeV) pairs of nucleons and antinucleons can be produced through particle collisions. But if baryon number is conserved at these temperatures, then the *net* baryon number density just equals today's baryon number density, suitably scaled. In other words, Eq.

(36.3) really deals with the *net* baryon density:

$$[\textit{photons} \,/\, \textit{net baryons}] = 10^8 \text{ to } 10^9. \quad (36.4)$$

Today's baryons are the remnants of the massive annihilation of baryons and antibaryons in the early universe.

So, the early universe carried a small excess of baryons and, because the universe is electrically neutral, a small excess of electrons (1 in 10^9 for each). The neutrino density of today's universe has not been measured, but it must be close to the photon number density (although they can't be equal, as neutrinos went out of thermal equilibrium at a different time/temperature than photons, and they also obey different statistics). Unless the universe was "created" with this excess of protons and electrons, then processes that violate B and L must be present in the early universe. We now describe how this might occur, although we will not present the numerical predictions of any models.

Grand unified theories

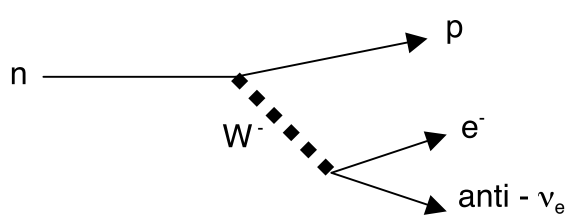
As they appear in reactions and decays, the fundamental interactions are characterized by parameters which we will call α_s, α_{em} and α_w. The magnitudes of each α can be obtained from reactions and decays, assuming a model for how the interaction is propagated between particles. In the photon and gluon exchange models described earlier,

$$\alpha_s \sim 1$$

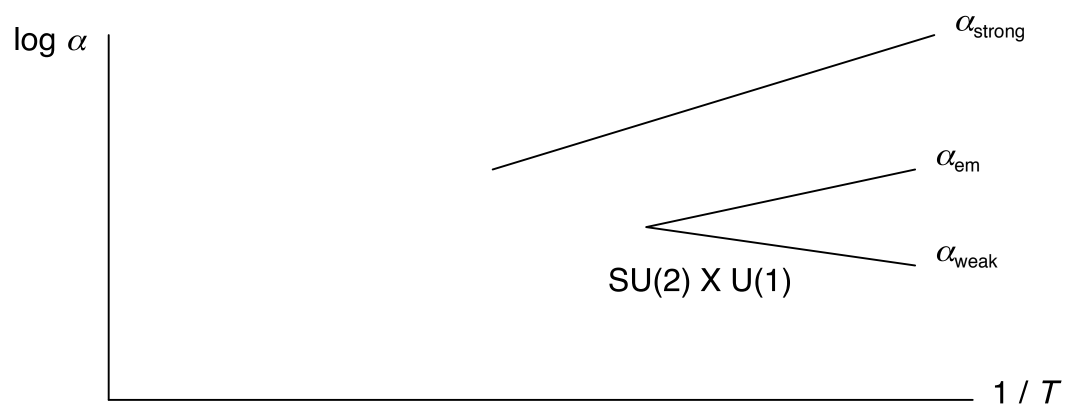
and

$$\alpha_{em} = 1 / 137 \qquad \text{(= the electromagnetic fine-structure constant } e^2 / [hc / 2\pi]\text{).}$$

The weak interaction is a little more subtle, because the carriers of the force have mass. In processes like neutron decay



the appearance of the W^- boson suppresses the probability of decay by a factor of m_W^2. When this suppression is taken into account, α_w is found to be not much different from α_{em}. Further, the parameters α are not strictly constant, but depend weakly on the momentum carried by the gauge boson. The temperature also affects the effective strength of the interactions. For the weak and electromagnetic interactions, α_{em} and α_w are predicted to be equal at a temperature $k_B T \sim 100$ GeV, the mass scale of the W and Z bosons, as illustrated in the following diagram. Note that the strong coupling term α_s is not equal to the electromagnetic and weak terms at this temperature.



Now, the equality of α_{em} and α_w under certain conditions is part of the unified theory of the weak and electromagnetic interactions, which has now been moderately well tested. In fact, the masses of the W and Z bosons were predicted from α_{em} and the effective strength of the weak interaction, within a suitable framework. The theory is denoted by the symmetry group SU(2) x U(1) and has gauge bosons:

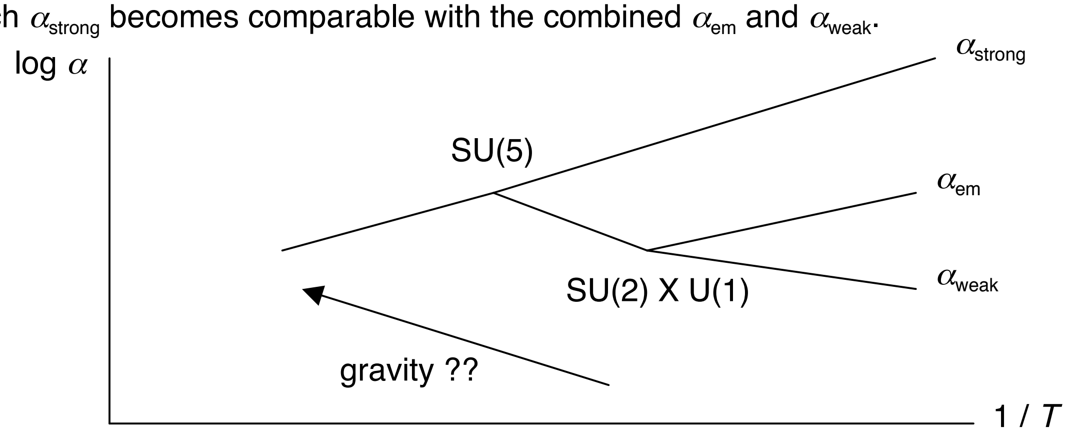
photon	massless
$W^{\pm}$	$mc^2 = 80.419 \pm 0.056$ GeV
Z^{o}	$mc^2 = 91.1882 \pm 0.0022$ GeV.

The particle spectrum of this theory includes another particle called a Higgs boson, whose predicted properties are described in most modern books on particle physics.

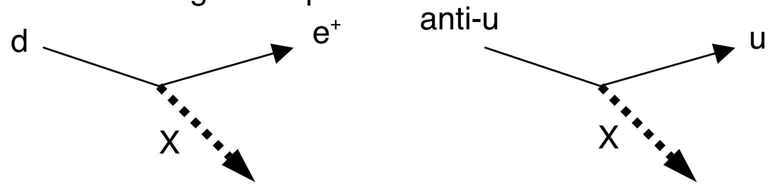
The strong interaction is not part of SU(2) x U(1). The simplest theory that includes the 8 gluons carrying the strong force between quarks is called SU(5), and includes among its gauge particles:

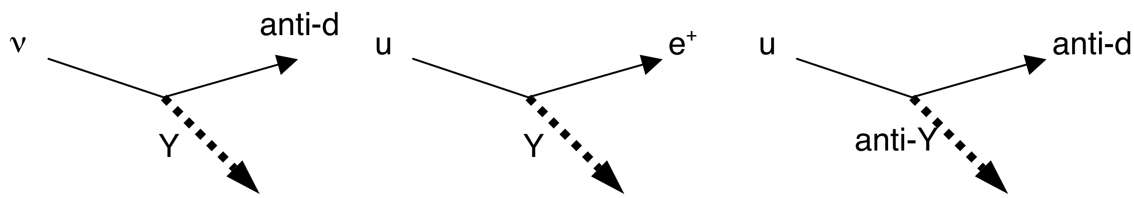
gluons	massless
$X^{\pm}$	$\sim 10^{15}$ GeV
$Y^{\pm}$	$\sim 10^{15}$ GeV
photon	massless
$W^{\pm}$	$mc^2 = 80.419 \pm 0.056$ GeV
Z^{o}	$mc^2 = 91.1882 \pm 0.0022$ GeV.

The masses of the predicted X and Y gauge bosons arise from the energy scale at which α_{strong} becomes comparable with the combined α_{em} and α_{weak}.

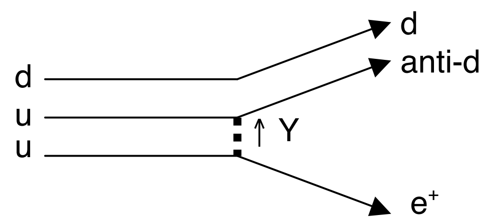


The X and Y bosons link quarks and leptons, violating both baryon number and lepton number in the process. With charges of Q_X = - 4/3 and Q_Y = - 1/3 (both in terms of *e*), processes like the following are expected to occur:





The contribution of the Y boson to the proton decay mode p → π^o + e^+ is



The anti-X boson can contribute through the annihilation of the two u-quarks (total charge = +4/3) to produce an (e^+) - (anti-d) pair. Note that *B* - *L* is conserved in this reaction, but not *B* + *L*:

	before	after
B - *L*	1 - 0 = 1	0 - (-1) = +1
B + *L*	1 - 0 = 1	0 + (-1) = -1

This grand unified theory then provides one mechanism for violating baryon number and lepton number simultaneously (Weinberg, 1979), although other models are possible. As first pointed out by Sakharov, there are a number of general conditions that must be met to generate a baryon asymmetry:

- the system must go out of equilibrium
- *CP* symmetry must be violated
- the asymmetry must not be removed by subsequent re-equilibration.

One mechanism for driving a system out of equilibrium is supercooling through a phase transition, whose possibilities include:

Grand unified theories

- asymmetry generated by *B*+*L* process is removed by re-equilibration
- asymmetry generated by *B*-*L* process is sustained

Electro-weak theories

- asymmetry may be produced non-perturbatively
- asymmetry is predicted by standard model, but is many orders of magnitude less than the observed value.