Physics 228, Lecture 23
Thursday, April 21, 2005

Elementary Particles. Ch. 44:2–3

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1 Conservation Laws

The interactions all obey the laws of conservation of energy, momentum, angular momentum, and electric charge, for which we have good grounds to believe are absolute conservations laws of nature. They also obey two other conservation laws, that of baryon number and of lepton number. There are reasonable theories that claim that it may be possible that these numbers are not conserved, or not separately conserved, but so far no observations of violations of these conservation laws have been observed.

The conservation of total lepton number may be broken down into three separate conservation laws, of electron number, muon number, and tau, each of which counts the number of that lepton and its corresponding neutrino, and subtracts the number of their antiparticles. Each of these three quantum numbers is approximately conserved (that is, conserved in most interactions), but there is now evidence that there are interactions which do not separately conserve these three numbers but only the total number of leptons (minus antileptons). This is connected to **neutrino mixing** and to the possible masses of the neutrino, and is a hot topic these days.

There are also conservation laws which are associated with simple symmetries. In fact, all conservation laws are associated with some symmetry. Momentum conservation is connected to translational symmetry === that is, the laws of physics are the same for two coordinate systems spatially displaced from each other. Angular momentum conservation is associated with rotational symmetry — the laws of physics don't care in which direction you place your x-axis. Energy is associated with translations in time.

There are three discrete symmetries which we now know are not exact symmetries of nature, though that came as a big surprize to physicists. One is mirror symmetry, known as parity (P). For most of physics, the laws of physics look the same in a mirror image as they do in the real world. Some paradoxes in decays led Lee and Yang[1], in 1956, to suggest that parity might not be a symmetry of nature and one should check the decays of cobalt 60, which was done by Madame Wu and collaborators in 1957, verifying that the symmetry is not exact and that the weak interactions violate parity conservation.

Another such approximate symmetry is charge conjugation (C), which says that if all the particles are exchanged for antiparticles, the physics is the same. Thus if an antiproton bound with a positron, the spectrum of the antihydrogen atom thus formed would be exactly the same as for ordinary hydrogen. But again the weak interactions violate this symmetry. For a while it was thought that the combination, CP is a good symmetry - that anti-cobalt in a mirror would behave just like real cobalt in real space. But in 1964 even that symmetry fell to Cronin and Fitch[2].

Finally, there is time reversal symmetry. The fundamental laws of physics seemed to be unchanged if one took a movie and played it backwards, even though macroscopic physics doesn't allow a splattered humpty-dumpty to rise up to an intact egg sitting on a wall. But time reversal symmetry is connected to CP symmetry. The framework by which we currently understand elementary particle physics insists that the combination of the three symmetries, TCP, is a good symmetry. That is, if you take a movie in a mirror, change all the particles to antiparticles, and play the movie backwards, the movie will obey the correct laws of physics!

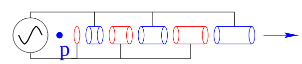
2 Accelerators

We are beginning to talk about particles which are not commonly found in nature. Muons were first discovered in the particle showers formed when cosmic rays hit the atmosphere. In the 1930's and 40's people who wanted to investigate unstable subnuclear particles began to develop machines that could accelerate charged particles to high energies, with the purpose of creating these particles and investigating their interactions at high energy. Last term we discussed the cyclotron, and found that one could accelerate particles to arbitrarily high energies with an alternating voltage of fixed amplitude and frequency, but in explaining how this worked we assumed the particles obeyed Newtonian physics in addition to Maxwell's laws. This will be okay

[1]Nobel prize, 1957
[2]Nobel prize, 1980

for protons up to about 20 MeV, but after that relativistic effects, which make the momentum unequal to mv, come into play, and the period of the circular orbit begins to increase. One can nurse these devices to produce protons with a bit more energy by working with bunches of particles, decreasing the frequency as the particles gain energy. Such a device is called a synchrocyclotron.

Another way to accelerate charged particles is with a **linac**, or **linear accelerator**. As in the region between the dees of a cyclotron, if we can arrange it that protons always find themselves headed towards a negative voltage and away from a positive one, they will be continuously speeded up. We can do this by arranging a long row of cylinders alternately connected to an AC power supply, as long as we have the spacing just right so that the proton always finds itself in the right position when the voltage is maximum. There is a two mile long linac at the Stanford Linear Accelerator Center in Palo Alto, California, which accelerates electrons to 50 GeV.



Linacs have the disadvantage that each charged particle gets only one boost from each accelerating spot, whereas particles in circular orbits can be accelerated many times by the same piece of equipment. That was why the cyclotron was such an efficient method before relativity gave problems.

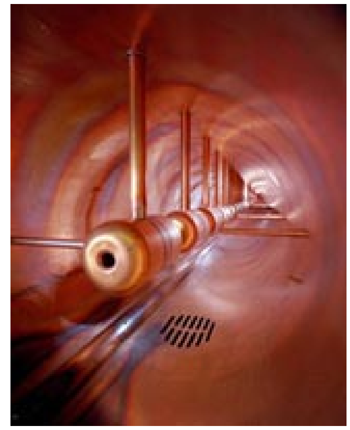
An alternative which proved much better able to achieve high energies than a synchrocyclotron is called the **synchrotron**. Bunches of particles are accelerated to a fixed energy by some other device and injected into a ring with a magnetic field of just the right strength to bend them in a circle with the radius of the ring. Inserted into this ring is a short "RF-cavity" which acts like a short section of a linac, boosting the energy of the particles *each time* they go through. To keep the radius of the circular motion constant, the magnetic field is increases in sync with the energy of the particles.

Today the highest energy accelerator in the world is the tevatron at Fermilab, in Illinois. It accelerates protons to an energy of one TeV, that is, 10^{12} eV. This is done with a chain of accelerators, starting with a Cockcroft-Walton device which ionizes hydrogen gas and accelerates it through a large potential difference[3].

[3]For a visualization of the path of a proton through the Fermilab system, see `http://www-bd.fnal.gov/public/index.html`

Overview of FermiLab

Cockcroft-Walton accelerator, 750 keV



Linac, 500 ft, 400 MeV

From there the beam enters a small linear accelerator, which injects the beam at 400 MeV into the booster synchrotron. At this point their speed is 0.713 c. After the booster ring is filled with 400 MeV protons, its field is increased and the protons accelerated to 8 GeV, moving at 0.993 c. Then they are transferred to the main injector. Some of the protons are then accelerated to 150 GeV, or $v = 0.99998c$. Other protons are crashed into a target which produces a whole lot of junk, including antiprotons. These antiprotons are cooled down, then accelerated also to 150 GeV. Then both particles are injected into the main ring of the tevatron, in opposite directions, where their energy is boosted to 996 GeV (not quite a TeV yet, but close!). Then $v = 0.99999956c$.

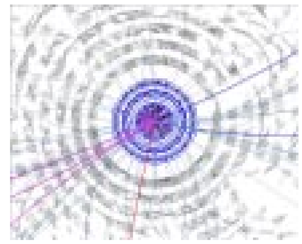
Booster synchrotron
8 GeV

Main injector.
p and $\bar{p}$ at 150 GeV

Tevatron, main ring 996 GeV p and $\bar{p}$.

Finally, in the middle of huge detectors, these beams of protons and antiprotons are each focussed to a diameter of about one millimeter and slammed into each other.

Here is a typical result — hundreds of particles emerging from one collision of a proton and antiproton:



Why colliding beams? Early accelerators were designed to shoot a beam of particles at a stationary target, and that is surely much easier than getting two beams to collide. But physicists are always trying to find out what happens at higher energy, and it is only the energy in the center of mass reference frame that counts. If two counterrotating 1000 GeV beams of p and $\bar{p}$ collide, the total energy available for interaction is 2000 GeV. How does this compare to one beam, say of $\bar{p}$, hitting a proton in a stationary target?

$$\begin{aligned}
E_{\bar{p}} &= 1000 \text{ GeV} \\
p_{\bar{p}}\, c &= \sqrt{(1000 \text{ GeV}) - m_p^2 c^4} = 999.9996 \text{ GeV} \\
E_p &= 0.9383 \text{ GeV} \\
p_p &= 0 \\
E_{\text{Tot}} &= 1000.9383 \text{ GeV} \\
p_{\text{Tot}}\, c &= 999.9996 \text{ GeV} \\
E_{\text{CM}} &= \sqrt{E_{\text{Tot}}^2 - p_{\text{Tot}}^2 c^2} = 43.3 \text{ GeV}
\end{aligned}$$

In the last step, we used the invariance of $E^2 - p^2c^2$, that is, it has the same value in all reference frames. We have evaluated it explicitly in the laboratory frame, but in the center of mass frame, $p_{\text{Tot}} = 0$, so it is just E_{CM}^2. So the colliding beams give us not twice the useful energy, but 46 times as much!

More generally, if a particle of mass m and total energy E_m hits a particle of mass M at rest,

$$E_{\text{Tot}}^{(\text{Lab})\,2} = (E_m + Mc^2)^2 = (Mc^2)^2 + 2Mc^2E_m + E_m^2,$$

while

$$\begin{aligned}
E^{(\text{cm})\,2} &= E_{\text{Tot}}^{(\text{Lab})\,2} - p_m^2c^2 = (Mc^2)^2 + 2Mc^2E_m + (E_m^2 - p_m^2c^2) \\
&= (Mc^2)^2 + 2Mc^2E_m + m^2c^4.
\end{aligned}$$

This explains Eq. 44.9 in the book.

3 Strange Particles

We have just reviewed the possibilities for experimenting with high energy collisions up to the highest energy today, which is jumping ahead of our story quite a bit. In the '40s and '50s, protons could be accelerated to 100's of MeV, and the expected pion found. There are three pions, π^+ and π^- with masses of 139.6 MeV, and π^0 with 135.0 MeV. The π^0 decays into two photons, but the $\pi^\pm$ decay into $\mu^\pm$ plus a (anti)neutrino. The muon decays as well.

$$\begin{aligned} \pi^- &\longrightarrow \mu^- + \bar\nu \qquad && (26\,\mathrm{ns}), \\ \mu^- &\longrightarrow e^- + \nu + \bar\nu \qquad && (2.2\,\mu\mathrm{s}). \end{aligned}$$

But all sorts of other unstable particles were produced, many with properties that seemed quite strange. When beams of pions were made, secondaries from other collisions, one found that two new particles were produced,

$$\pi^- + p \longrightarrow K^0 + \Lambda^0.$$

The masses are $M_K = 497.7$ MeV, $M_\Lambda = 1115.6$ MeV. The Λ^0 is a baryon, decaying into nucleons and pions:

$$\Lambda^0 \longrightarrow p + \pi^-, \qquad \text{or} \quad \Lambda^0 \longrightarrow n + \pi^0$$

These particles seemed strangely long lived, with $\tau_\Lambda = 0.26$ ns. Compare that to another particle produced, the Δ^+, with mass 1232 MeV and a half-life of 10^{-23} s, and you see the Λ^0 is practically stable.

Another strange feature is that Λ^0 were never produced without an accompanying "strange" new particle, one never saw

$$\pi^- + p \longrightarrow \pi^0 + \Lambda^0 \quad \text{never happens!.}$$

Both of these strangenesses can be explained if we postulate a new almost conserved quantity, called **strangeness**, and claim the K^0 has one unit of it and the Λ^0 has -1 units of it. All the particles we knew of before have no strangeness. Strangeness is not absolutely conserved, but is violated only by the weak interactions, which means the decay (which violates strangeness conservation) occurs only very slowly. The production process does not violate strangeness, because the total strangeness in both the initial and final states in

$$\pi^- + p \longrightarrow K^0 + \Lambda^0$$

is zero.

There are many other particles with strangeness. Similar to the Λ^0 are the three sigma particles, Σ^-, Σ^0, and Σ^+, each of which, like the Λ^0, has strangeness -1. The strangeness 1 K^0 also has a sister particle with charge e, the K^+. So another possible result of a π^- p collision is

$$\pi^- + p \longrightarrow K^+ + \Sigma^-.$$

The Σ^- decays into a neutron and a π^- with a lifetime of 0.15 ns.