

Evidently L_e is conserved in this reaction. We need not consider L_μ and L_τ as the only leptons in the reaction are from the first generation.

Taking another example:

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e. \quad (4.8)$$

In this case the total electron-number (L_e) and the total muon-number (L_μ) *separately* must be the same before and after the reaction:

$$\begin{array}{rcccccc} \nu_\mu & + & e^- & \rightarrow & \mu^- & + & \nu_e \\ L_e & 0 & + & 1 & = & 0 & + & 1 \\ L_\mu & 1 & + & 0 & = & 1 & + & 0. \end{array}$$

We could consider many other reactions that would all demonstrate the conservation of the various lepton numbers. This has become a well established rule in particle physics amply confirmed by experiment and with a secure theoretical grounding as well.

LEPTON NUMBER CONSERVATION

The total electron-number, muon-number and tau-number are
separately conserved in all reactions

Note the similarity between this rule and the conservation of electrical charge.

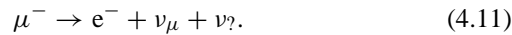
By this stage you may have the uncomfortable feeling that all we are doing is describing what is essentially a very simple thing in a complex way. In the last chapter we simply said ‘the weak force must maintain the number of leptons of each generation that are involved in a reaction’. Now we are conserving three different lepton numbers.

This would be a serious criticism if it could not be shown that lepton number conservation leads us into new physics that we could not otherwise explain.

5.1.2 Mystery neutrinos

There are some reactions that seem to violate the rule that we now call lepton number conservation. One of the reactions that is giving us

trouble is:



If we look at this reaction in terms of lepton number then something interesting emerges:

$$\begin{array}{rccccccc} \mu^- & \rightarrow & e^- & + & \nu_\mu & + & \nu? \\ L_\mu & 1 & = & 0 & + & 1 & + & ? \\ L_e & 0 & = & 1 & + & 0 & + & ? \end{array}$$

The assignment of lepton number for the mystery neutrino is unclear as we have not identified what sort of object this is. One thing seems very likely from this however—it *must have muon-number = 0*. If this were not the case, the muon-number conservation law would certainly be violated.

Notice also that initially the electron-number was zero, and then the decay created a particle with an electron-number of 1. The total on the right-hand side would be zero if our mystery neutrino had electron-number = -1 .

Now this *looks* like a mathematical invention. Certainly if the ‘?’ in the electron-number row were -1 then the totals would balance, but this alone does not make it physically correct. Let us for the moment suppose that our mystery neutrino has electron-number -1 and see if that helps to explain any other puzzles.

Another reaction that has been giving us trouble is the β decay of some nuclei:



This reaction is due to the more basic quark reaction inside the neutron:



When we discussed this reaction in the previous chapter I suggested that all was not quite as simple as it seemed. If we examine the reaction in terms of lepton number:

$$\begin{array}{rccccccc} d & \rightarrow & u & + & e^- \\ L_e & 0 & \neq & 0 & + & 1. \end{array}$$

then we see that L_e is not conserved. This dilemma can be solved by suggesting that our mystery neutrino is produced in the reaction as well:

$$\begin{aligned} d &\rightarrow u + e^- + \nu? \\ L_e \quad 0 &= 0 + 1 + -1. \end{aligned}$$

Experimentally it is easy to show that the mystery neutrino is produced in this reaction.

Historically it was in order to solve another puzzle connected with reaction (4.9) that Pauli first suggested the existence of the neutrino type of particle (see section 8.2.4).

Now we have made real progress. The presence of the mystery neutrino in (4.9) was deduced entirely through trying to conserve electron-number. This is concrete evidence that the property exists and is not just an invention of physicists. The next thing to do is see how this neutrino reacts with matter.

We are used to neutrinos reacting with the nuclei of atoms, so we can imagine an experiment in which the mystery neutrinos are allowed to pass through a block of matter in order to see what reactions take place. If this experiment were to be done² then something quite remarkable would be discovered. A totally new particle would be produced!

$$\nu? + p \rightarrow n + e^+. \quad (5.1)$$

The e^+ has a positive electrical charge equal to that of the proton—but it is not a proton as the mass can be measured rather easily and found to be exactly the same as the mass of the electron.

This, as one might imagine, is an important discovery. Historically, the existence of this particle has been known for some time as it was discovered, in rather different circumstances to those described, in 1933³. It has been named the *positron*.

Within the context of our discussion, the significance of the positron is that it must have $L_e = -1$ (like the mystery neutrino). This follows from applying the conservation law:

$$\begin{aligned} \nu? + p &\rightarrow n + e^+ \\ L_e \quad -1 + 0 &= 0 + -1. \end{aligned}$$

Notice that the proton and neutron have lepton numbers of 0: they are composed of quarks.

At this point we need to stop and consolidate. This has been a complex section introducing some new ideas and we need to ensure that they have all sunk in before we can go any further.

COFFEE POINT
stop reading
make a cup of coffee
sit and think over the following points

- We have introduced the idea of internal properties to describe the difference between particles that have no other obvious physical difference;
- the internal property that distinguishes the generations of leptons is called lepton number;
- the total lepton number is a conserved quantity in many reactions;
- some reactions do not obviously conserve lepton number;
- we can extend the idea of lepton number by suggesting that the mystery neutrino produced in muon decay has $L_e = -1$;
- this new neutrino also turns up in β decay where it was not expected and helps to solve the generation problem that seemed to occur with this reaction;
- if this new neutrino is passed through matter, then it can react with a proton to produce a positively charged particle with the same mass as the electron—this particle has been named the positron;
- positrons also have electron-number -1 .

This is a convincing argument for the physical reality of internal properties.

5.2 Positrons and mystery neutrinos

It seems as if we have introduced a new generation of leptons. As well as the first generation (e^- , ν_e), in which both particles have $L_e = 1$, we have the positron and the mystery neutrino, both of which have $L_e = -1$. However, by definition, a new generation would have to have $L_e = 0$ and a new type of lepton number to identify it. What we have here are