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# Very Elementary Particle Physics

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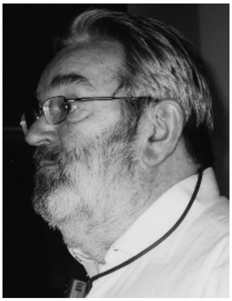
**Abstract** This address was presented by Martinus J.G. Veltman as the Nishina Memorial Lecture at the High Energy Accelerator Research Organization on April 4, 2003, and at the University of Tokyo on April 11, 2003

## Introduction



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Today we believe that everything, matter, radiation, gravitational fields, is made up from elementary particles. The object of particle physics is to study the properties of these elementary particles. Knowing all about them in principle implies knowing all about everything. That is a long way off, we do not know if our knowledge is complete, and also the way from elementary particles to the very complicated Universe around us is very very difficult. Yet one might think that at least everything can be explained once we know all about the elementary particles. Of course, when we look to such complicated things as living matter, an animal or a human being, it is really hard to see how one could understand all that. And of course, there may be specific properties of particles that elude the finest detection instruments and are yet crucial to complex systems such as a human being.

In the second half of the twentieth century the field of elementary particle physics came into existence and much progress has been made. Since 1948 about 25 Nobel prizes have been given to some 42 physicists working in this field, and this can be seen as a measure of the amount of ingenuity involved and the results achieved. Relatively little of this is known to the general public.

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M. J. G. Veltman: *Very Elementary Particle Physics*, Lect. Notes Phys. **746**, 371–392 (2008)
DOI 10.1007/978-4-431-77056-5_17

In this short account a most elementary introduction to the subject is presented. It may be a small step to help bridging the gap between the scientific knowledge achieved and the general understanding of the subject.

## Photons and Electrons

Photons are very familiar to us all: all radiation consists of photons. This includes radio waves, visible light (from red to dark blue), X-rays, gamma rays. The first physics Nobel prize, in 1901, was given to Röntgen, for his discovery of X-rays or röntgen rays. The 1921 physics Nobel prize was awarded to Einstein for his discovery that light is made up from particles, photons. Einstein is most famous for his theory of relativity, but it is his discovery of photons that is mentioned by the Swedish Academy. Indeed, many think that this is perhaps his most daring and revolutionary discovery!

The difference between all these types of photons is their energy. The photons of radio waves have lower energy than those of visible light (of which red light photons are less energetic than blue light photons), those of X-rays are of still higher energy, and the gamma rays contain photons that are even more energetic than those in X-rays. In particle physics experiments the photon energies are usually very high, and then one deals with individual photons. The energy of those photons starts at 100,000,000,000 times that of the photons emitted by portable phones.

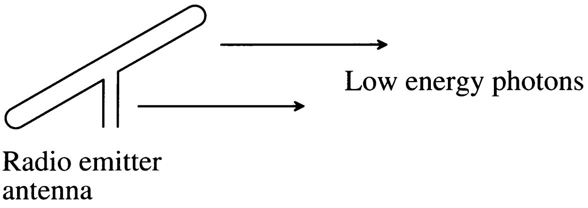


**Fig. 17.1**

Especially at lower energies the number of photons involved is staggering. To give an idea: a 1 watt portable phone, when sending, emits roughly 10,000,000,000,000,000,000,000 photons per second. Together these photons make the wave pattern of radio waves. Also in visible light the number of photons is generally very large. Interestingly, there exist devices, called photo-multipliers that are so sensitive that they can detect single photons of visible light. The photons of visible light are one million times as energetic as those emitted by a portable phone, and while the number of photons emitted is correspondingly lower the amount is still enormous.

Electrons are all around us. They move in wires in your house, make light, and function in complicated ways in your computer. They also make the pictures on your TV or computer screen. In the tube displaying the picture electrons are accelerated and deflected, to hit the screen thereby emitting light.

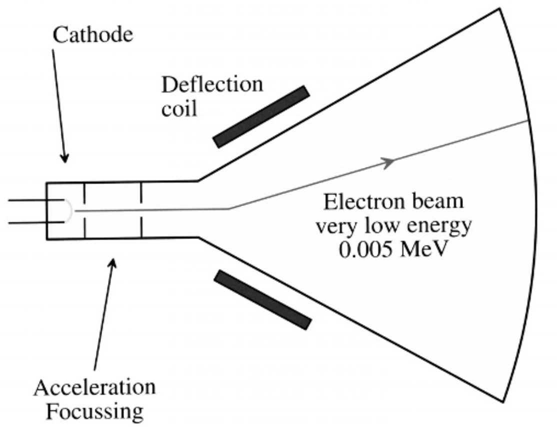


**Fig. 17.2**

In the tube, on the left in the picture, a piece of material called the cathode is heated. As a consequence electrons jump out of the material, and if nothing were done they would fall back. However, applying an electric field of several thousand volt they are pulled away and accelerated. Then they are deflected, usually by means of magnetic fields generated by coils, deflection coils. They make the beam of electrons move about the screen. There they paint the picture that you can watch if you have nothing better to do.

Thus inside your TV tube there is an accelerator, although of rather low energy as accelerators go. The energy of the electrons is expressed in electron-Volts. An electron has an energy of one electron-Volt (abbreviated to eV) after it has been accelerated by an electric field of 1 Volt. In a television tube the field may be something like 5000 V, thus the electrons in the beam, when they hit the screen, have an energy of 5000 eV. In particle physics the energies reached are much higher, and one uses the unit MeV. One MeV is one million eV. Thus the electrons inside the TV tube have an energy of 0.005 MeV. Try to remember that unit, because it is used everywhere in particle physics. Related units are GeV (1 Giga eV = 1000 MeV) and TeV (1 Tera eV = 1000 GeV).

## Making New Particles

In order to make particles one must first make an energetic beam of electrons or protons. Protons can be found in the nucleus of an atom together with neutrons. The simplest nucleus is that of hydrogen, it contains only one proton. The picture shows a hydrogen atom, one proton with one electron circling around it. The electron is negatively charged, the proton has exactly the same charge but of the opposite sign. The total charge of a hydrogen atom is the sum of these two and Is thus zero, it is electrically neutral.

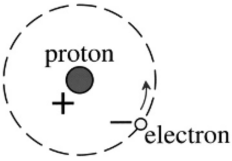


**Fig. 17.3**

The first step then is to take a box filled with hydrogen. Subsequently a strong spark, an electric discharge, is produced in that box. This amounts to a beam of electrons moving through the hydrogen. When it meets a hydrogen atom on its way the electron is knocked out of the atom, and there results an electron and a proton drifting in that box. Ionization is the name given to the process of stripping electrons from an atom.

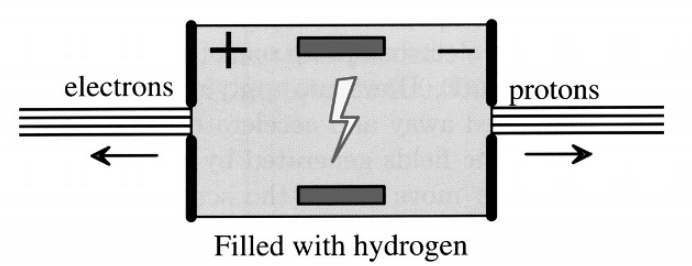


**Fig. 17.4**

The next step is to apply an electric field. If the field is positive on the left then the electrons are pulled to the left and the protons, having the opposite charge, are pulled to the right. Making a little window (of some thin material) the protons emerge on the right hand side and one has a proton beam. Likewise one has en electron beam on the left hand side, but this is not an efficient way to make electron beams. One can do it better as shown by the TV tube.

To produce new particles one must create a minuscule bubble of concentrated energy. From Einstein's equation $E = mc^2$ we know that matter is a form of energy, and in order to make a particle of some mass one must have an energy bubble of at least that much energy. The bubble will decay into whatever is possible, sometimes this, sometimes that. But always, the energy equivalent to the sum of the masses of the particles that it decays into is less than the initial energy of the bubble. That is why particle physicists want forever bigger accelerators. Those bigger machines create ever more energetic bubbles, and very heavy particles, not seen before, may appear among the decay products of those bubbles.

To create a bubble of high energy the beam of protons coming out of the ionization chamber is accelerated to high energy, and then the protons are smashed into other particles, for example particles in an atomic nucleus.

Thus one simply shoots the beam into a suitable material, a target. Whenever there is a collision of a particle in the beam with a nucleus a bubble will form and that bubble will decay into all kinds of particles. In this way new particles can be found. Those particles, themselves little bubbles of energy, are usually unstable and they decay after a little while and that is why they are not seen in the matter around us. There are only a few stable particles, mainly photons, electrons, protons and neutrinos.

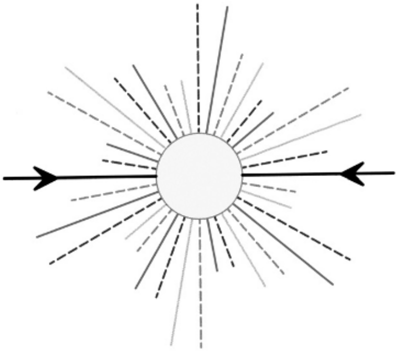


**Fig. 17.5**

The new particles found are given names, and their properties are studied. In the early days these particles were called mesons. For example one finds copiously $\pi$-mesons, or briefly pions, particles with a mass about 260 times bigger than the electron mass. Those pions decay mostly into a muon (a $\mu$-meson, a particle whose mass is about 200 times that of the electron) and a neutrino ($\nu$, mass 0). The muon, while relatively long-lived, decays in an electron, a neutrino and an anti-neutrino. Anti-particles have almost the same properties as particles (they have the same mass, but opposite charge), but that will be discussed later. Often they are designated by placing a bar above the symbol, for example one writes $\bar{\nu}$ for an anti-neutrino.

Those things can already be seen using accelerators producing beams of moderate energy. Let us quote some numbers. The electron mass has an energy equivalent of 0.5 MeV, and a $\pi$ (pion) has a mass of 135 MeV. The $\mu$ (muon) has a mass of 105 MeV. Accelerators with beams of protons with an energy of 1 GeV = 1000 MeV have no trouble creating those particles. These particles are often electrically charged, positive or negative. The charge is usually measured in units equal to minus the charge of the electron, thus the electron has charge $-1$. The pion for example occurs in three varieties: $\pi^+$, $\pi^-$ and $\pi^0$, with charges $+1$, $-1$ and 0. The charged pions decay into a muon and a neutrino: $\pi^+ \rightarrow \mu^+ + \nu$ and $\pi^- \rightarrow \mu^- + \nu$. As indicated, the muons appear in two varieties, the $\mu^+$ and the $\mu^-$. There is no neutral muon. In every process seen up to now charge is always strictly conserved, so a negative pion decays into a negative muon (and a neutral neutrino), while a positive pion will always decay into a positive muon.

So let us now consider the whole situation such as can be found at CERN, Geneva. In 1959 an accelerator of 30 GeV = 30,000 MeV was switched on. See the figure further down. First there is an ionization chamber, producing a beam of protons. With electric fields of moderate value those protons are accelerated slightly and focussed into a tight beam. This beam is let into a big circular pipe, diameter 200 m. All around that pipe magnets are placed, and magnetic fields are made such that the beam is curved and remains inside the pipe. At certain points along the beam pipe there are segments with an electric field, and when the beam passes through such a segment the particles receive a kick and their energy increases. The beam goes around many times, and the magnetic fields are increased gradually to keep the ever higher energy protons inside the beam pipe. At some point the magnetic fields reach their limit, and then no more acceleration is possible. At that point the beam is extracted from the beam pipe and directed to a target. In the resulting collisions many particles will be produced. With various methods (magnetic fields, shielding with certain openings) those particles that one wants to study are selected, focussed into beams (called secondary beams) and directed into detectors for further study. Of course, this can only be done with particles that live sufficiently long and do not decay halfway in the process. There are several such particles, among them pions. Thus at CERN there were secondary pion beams with which experiments could be done. In this way the precise properties of pions were established.

At that time the detectors used mostly were bubble chambers and spark chambers, each with their advantages and disadvantages. They are described in the next chapter.

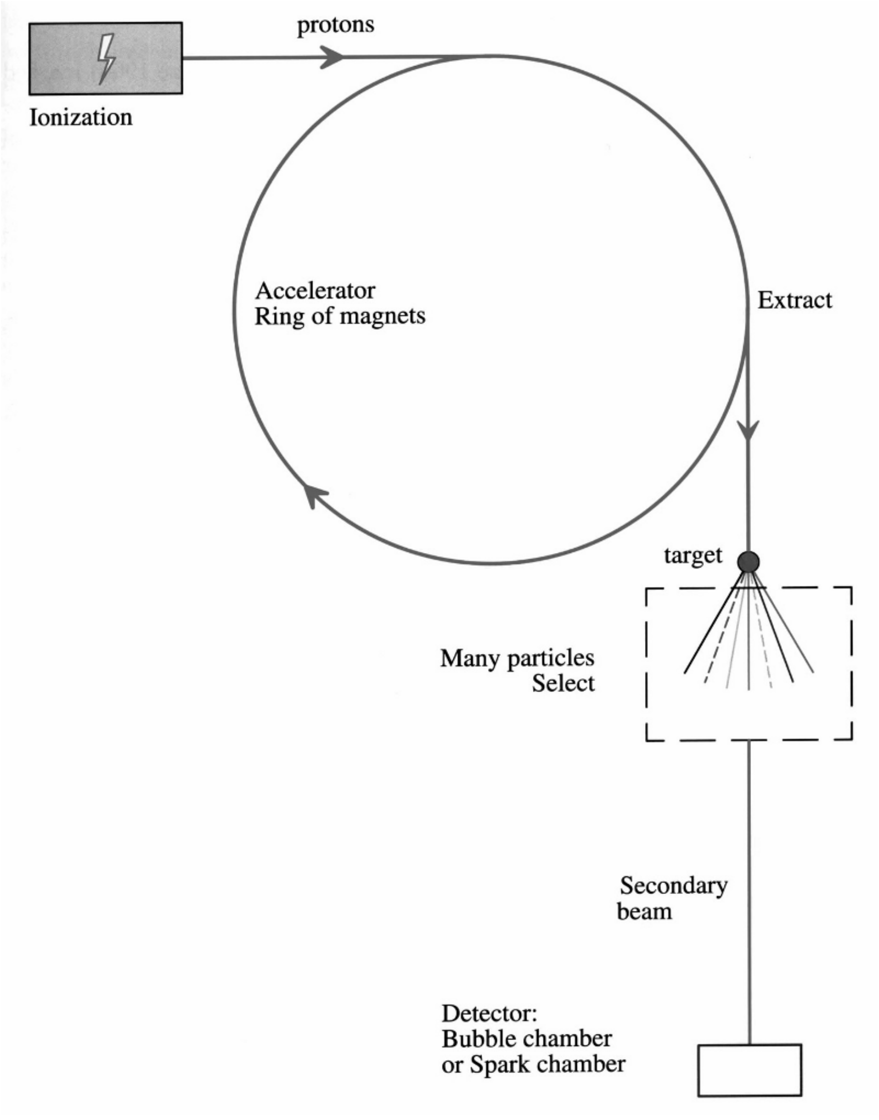


**Fig. 17.6** Particle physics accelerators. The diameter of the machine constructed at CERN (called PS) in 1959 is 200 m. The energy reached is 30 GeV = 30,000 MeV. At Fermilab near Chicago: diameter 2 km, energy 1 TeV = 1000 GeV

## Detectors

The invention of the bubble chamber by Glaser (Nobel prize 1960) marked the beginning of modern experimental particle physics. In a bubble chamber some liquid is kept near the boiling point, and (charged) particles moving through the liquid ionize atoms or molecules (knocking off electrons) on their path. As a consequence of these disturbances small boiling bubbles form along the track. Next a picture is taken, and the particle reactions can be studied in detail. To identify the sign of the charge of the particles passing through the bubble chamber a magnetic field is generated by means of coils near the chamber. The particle tracks will be curved due to this magnetic field, and positively charged particles will curve in the opposite way compared to negatively charged particles. Also, from the degree of curvature of the tracks one obtains information about the velocity of the particles. It should be emphasized that electrically neutral particles make no tracks, they are observed only indirectly.

In using the bubble chamber the material of the bubble chamber functions as a target. A beam of particles coming from an accelerator is sent into the bubble chamber, and the particles in the beam may collide with the atoms in the fluid. Usually these collisions are with the nuclei. The figure shows an example of a simple bubble chamber picture.

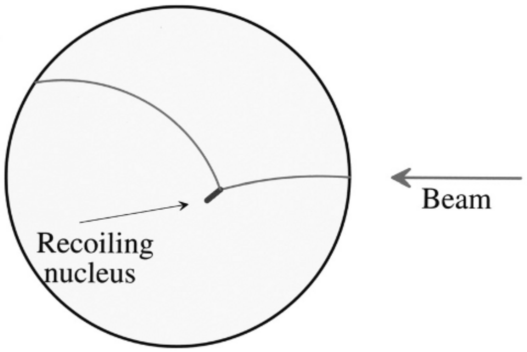


**Fig. 17.7**

Bubble chambers have a big disadvantage: they are slow. The process of bringing the fluid to the boiling point, taking a picture and then moving away from the boiling point is relatively slow (a few seconds). On the other hand the pictures are quite detailed, and allow a rather precise analysis.

Spark chambers consist of a number of metal plates, mounted parallel to each other with some well chosen gas in between. Particles passing through the gas result in ionization, and if one supplies a high voltage between the plates there will be sparks precisely at the place where the particle passed. Usually there is no magnetic field, so the tracks are not curved.

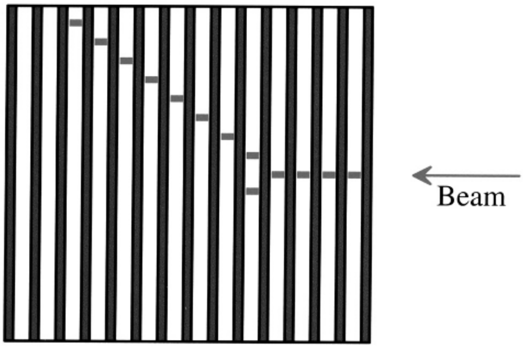


**Fig. 17.8**

The location of the track is also much less precisely defined. In the picture an event analogous to the above bubble chamber event is depicted. In this case the material in the plates functions as a target; events originating in the gas are much less likely simply because the gas has little density compared to the metal.

There are two advantages to the spark chamber over the bubble chamber. First, by using heavy metal plates (that are functioning as a target) one may have a really massive target, which is of advantage if one wants to study particles that react only rarely. Neutrinos are such particles, they interact so rarely that for example neutrinos from the sun usually have no trouble passing through the earth.

## The 1963 Cern Neutrino Experiment

The second advantage of spark chambers is that they can be triggered. By means of various techniques, involving other types of detectors, one may first establish that some event is of interest and only put voltage on the plates for those cases. In other words, one may make a selection in the type of events and concentrate on those of interest.

The introduction of spark chambers made neutrino physics possible. One could then have so much target material that the possibility of a neutrino interacting with the material became large enough to make experiments possible. The basic idea for such an experiment was due to Schwartz, who then together with Lederman and Steinberger did the very first experiment (Nobel prize 1988) at the Brookhaven National Laboratory, Long Island, USA. In 1963 a neutrino experiment was done at Cern and the figure shows the general layout. A big improvement compared to the earlier Brookhaven experiment was a horn, invented by van der Meer (he did get a Nobel prize later but not for this invention). That horn focussed the pions coming from the target, and that increased greatly the intensity of the pion beam coming out of the horn. Pions decay, principally into a muon and a neutrino, and letting them

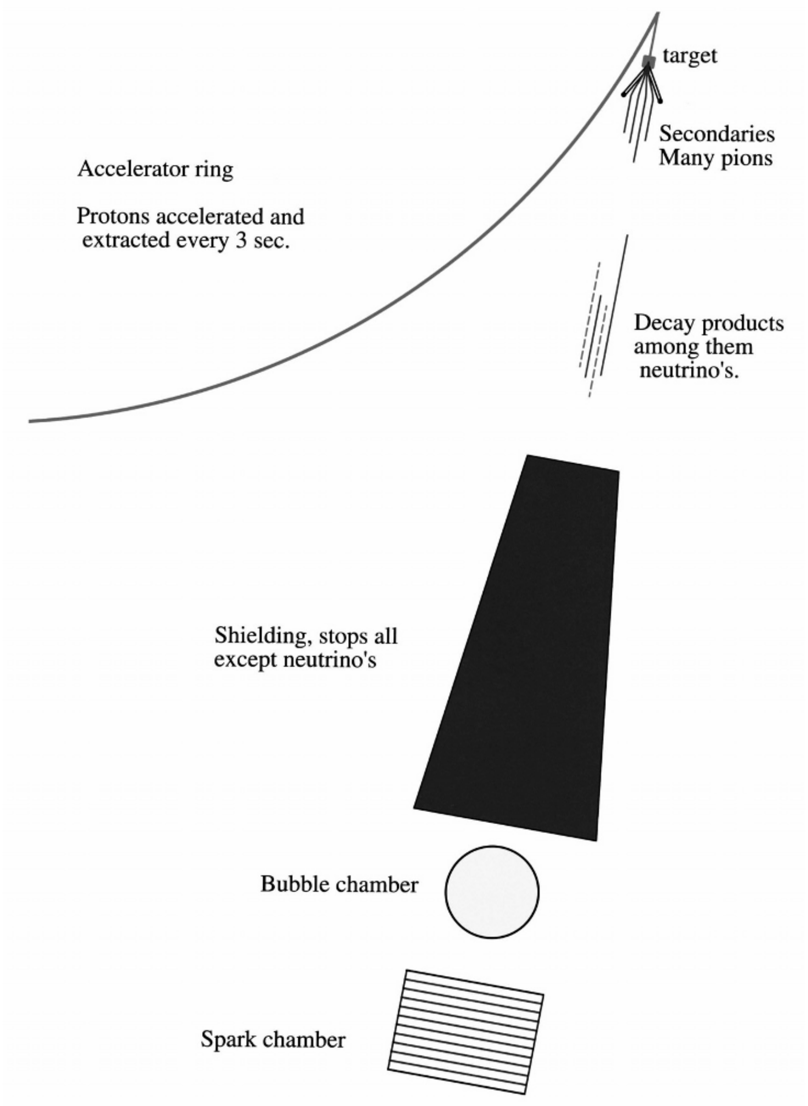


**Fig. 17.9**

pass some distance many will decay. Gradually the pion beam changes in a mixture of muons and neutrinos (plus other stuff coming from the target). The subsequent massive amount of shielding (some 25 m of steel) stopped all particles except the neutrinos. Thus almost exclusively neutrinos passed through the bubble chamber and the spark chamber positioned behind that shielding. From time to time one of them would interact with the material in either bubble chamber or spark chamber.

The bubble chamber was installed although one had little hope of seeing any neutrino induced events. In the first run 460,000 pictures were taken and luckily, about 240 events were seen. Without the horn one would very likely have had only few events, if any.

The spark chambers did better, as there was so much more material. Also, one did not have to scan many pictures, the spark chambers were triggered only if one knew, through other type detectors, that some charged particles came out of the chamber. Some 2000 events were seen on that many pictures. The numbers mentioned here are for the first run, the experiment ran for extended periods over many years.

One of the bubble chamber pictures generated much interest for reasons that cannot be explained here. The following figure shows the event, faithfully copied from the actual picture.

The neutrino beam entered from the right. After the collision several particles came out, and there was also a recoiling nucleus (or whatever remained of it after the collision). One of the particles produced was a negatively charged muon; it can be recognized by the fact that muons are charged particles that interact relatively rarely. In this picture the muon actually leaves the chamber without interacting. The remaining tracks are from electrons and positrons. A positron is precisely like an electron, however it has a positive charge. It is the anti-particle from the electron, one could thus also speak of an anti-electron. Except for what seems to be just one positron (in the middle, below) and one single electron (perhaps an electron kicked out of an atom, see arrow) one observes only pairs, electron-positron pairs. Such pairs are created by energetic photons as will be discussed in the next chapter.

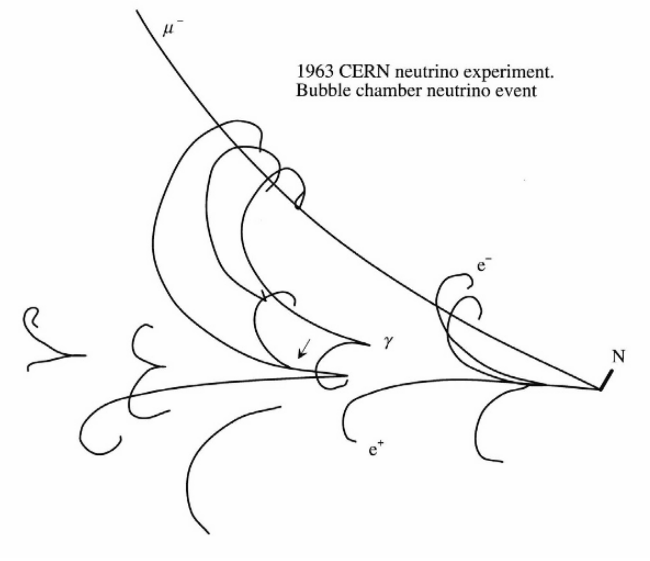
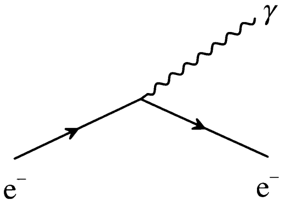


**Fig. 17.10**

## Feynman Rules

In 1948 great progress was made in the theory of elementary particles. Feynman introduced his diagram technique, and without that technique the theory would not have advanced to the point that it is today. Here is the idea.

In the antenna of a radio (or television) emitter electrons move back and forth inside the antenna. While doing so they emit photons, making the radio waves. The figure (called a vertex) depicts this process. An electron comes in from the left, emits a photon and continues.



Now the details of the process of emitting radiation by an electron are known since a long time, and they can be calculated in all precision. Thus corresponding to this picture there is a precise mathematical expression giving the numerical value for this process. Feynman made this into a very neat package. He gave a simple recipe whereby, given a diagram, one could write down very easily the corresponding mathematical expression from which the amount of radiation by the electron could be computed. The arrow in the electron lines gives the flow of (negative) charge. The beautiful thing about these diagrams is that they have a strong intuitive appeal.

Here is the next situation. On the receiver side, photons interact with the electrons in the antenna and make them move, thus generating currents. This is depicted by the diagram shown. It is very much like the previous diagram, except the photon is now incoming rather than outgoing. And again, there exists a mathematical expression that can be written down easily and that gives the precise strength for this process. Just looking at it one observes that the second diagram can be obtained from the first by moving the photon from out to in. This procedure is called crossing, a property of Feynman diagrams. Moving a line from in to out or the other way around gives another process that then indeed exists. This leads to remarkable things.

Taking the last diagram and moving the incoming electron to be outgoing one obtains the diagram shown here. In this diagram one incoming photon becomes a pair of an electron and something else that must be very close to an electron, except the arrow points the opposite way. There is a flow of negative charge inwards, which must be interpreted as a flow of positive charge outwards. Thus the charge of that particle is opposite to that of the electron. This particle is a positron, the anti-particle of the electron. With this interpretation there is agreement with another fact of nature: charge is always conserved. If one starts with zero (the charge of the

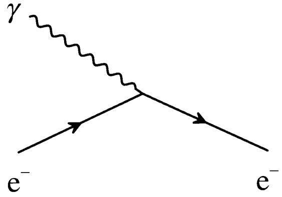


**Fig. 17.11**

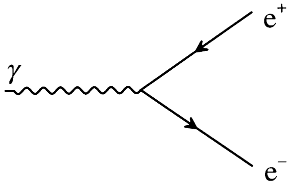


**Fig. 17.12**

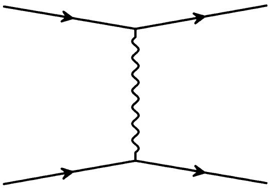


**Fig. 17.13**

photon) then one must end with zero (the charge of the electron plus that of the positron).

In the bubble chamber picture shown in the previous chapter several positrons appear. The photons, being neutral, are invisible, but they become electron-positron pairs that can be seen. They need not be symmetrical, one of the particles may come out faster than the other. The bubble chamber picture was taken in 1963, the positron was seen for the first time in 1930, by Anderson working at the California Institute of Technology (Nobel Prize 1936).

The diagrams shown above can be seen as elements that can be used to depict more complicate processes. For example, an electron can emit a photon that is then absorbed by another electron. In this way electrons can exchange a photon. In the process they deflect. Some innovative person has coined the example of two ice-skaters where one of them throws a sack of sand to the other. You can imagine the path of the skaters, they will deflect at the point were the exchange is made.

This process, exchange of a photon, is represented by the diagram shown. One speaks of Coulomb scattering. As always, having the diagram it is quite simple to write the corresponding mathematical equation, and there is no difficulty in calcu-

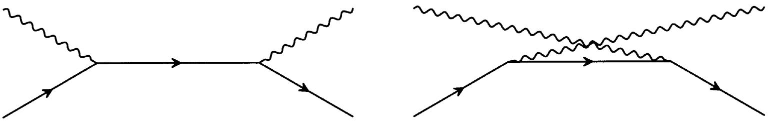


**Fig. 17.14**

lating all details. In our analogy all depends on the amount of sand in the sack; in the electron case the properties of the photon exchanged varies from case to case according to some probability pattern. One can also compute this, which then gives the relative probability of this or that photon exchanged.

Another observed process is Compton scattering (Nobel prize 1927). A photon may hit an electron and then subsequently that electron may emit a photon. That second photon needs not be of the same energy as the incoming photon. For example, a blue light photon could come in and the outgoing photon could be a red one. There are actually two diagrams here, because it is also possible that the electron first emits a photon and then later absorbs the incoming photon.

## Weak Interactions

In 1896 Bequerel discovered strange radiation, which was later understood as due to the decay of the neutron (Nobel prize 1903):

$$\text{neutron} \rightarrow \text{proton} + \text{electron} + \text{anti-neutrino} \qquad (17.1)$$

Today this is called $\beta$-decay. In shorter notation this can be written as:

$$\mathrm{N} \rightarrow \mathrm{P} + \mathrm{e}^- + \bar{\nu} \qquad (17.2)$$

The bar above the $\nu$ denotes the anti-particle. It took a long time, till about 1957, to understand this process in detail. Now we can write a diagram corresponding to this process, and we also know the corresponding equations. So we can say precisely how often the neutron decays with the electron going in some definite direction with respect to the proton. For example, starting with a neutron at rest, we can give the probability that after the decay the electron moves away opposite to the proton. Or that they come out at right angles. Looking to just one decay nothing can be said, but looking to, say, 100,000 decays we can pick out those cases that have the requested configuration (proton and electron opposite for example). If the probability for that to happen is 0.2$, then we will see that happen in roughly 200 cases. That is the way these things work, and for $\beta$-decay we can compute it all.

So, here is the diagram. There is one new element in this: the arrow for the neutrino is pointing inwards, like for a positron. The neutrino has no charge, thus

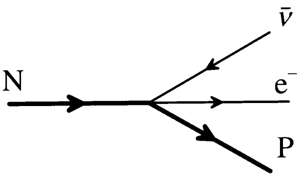


**Fig. 17.15**

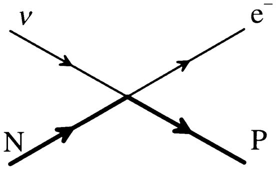


**Fig. 17.16**

there is no charge flow associated with this. Here the arrow is effectively used to indicate that we are dealing with an anti-particle.

From this process another may be obtained by means of crossing. Moving the anti-neutrino to the incoming side, whereby it becomes a neutrino, we find the process:

$$\nu + \mathrm{N} \rightarrow \mathrm{P} + \mathrm{e}^- \tag{17.3}$$

This is something that can be seen in a neutrino experiment as that at CERN in 1963. An incoming neutrino may hit a neutron in some nucleus, and then an electron and proton should come out. The electron is easy to recognize so this type of event should be recognized without difficulty. Moreover, since we know all about the mathematical expression corresponding to this diagram we can even predict how often this should happen. Indeed, events like this have been observed in the neutrino experiment in the amount predicted. So far, so good.

There is a serious theoretical difficulty however with this process. In a neutrino experiment the energy of the incoming neutrino is below 10 GeV = 10,000 MeV. This is a relatively low energy as these things go. But theoretically one can also compute this process for higher and higher energy, and then things go wrong. As the energy of the neutrino is made larger the probability for this process to happen increases fast (on paper), to grow to impossible values. By impossible we mean that the probability exceeds one. That would imply, idiotically, that one would see more of these events than neutrinos in the beam. One must go to very high energy neutrinos before this happens, but it does. There is (theoretically) trouble.

We may look at the analogous case for electrons and photons. The diagram for scattering of an electron from an electron has been given before (Coulomb scattering) and there is no problem. Let us therefore try something similar. We invent a new (hypothetical) particle to make a diagram that looks like the Coulomb scattering diagram. There is one big difference. Since charge must be conserved always the

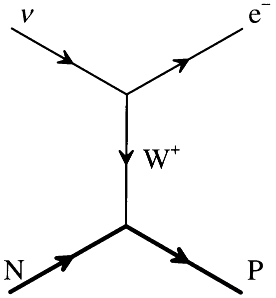


**Fig. 17.17**

new particle, called a vector-boson and denoted by W, must have a positive charge. This can be seen at the neutrino side: the neutrino chages into a negatively charged electron and a W, thus the charge of the W must be the opposite of that of the electron, i.e. positive, like the positron charge. This positive W then combines with the neutron (no charge) to become a proton (positive charge). The way we have done it the arrow in the W line denotes the flow of positive charge.

Indeed, considering now the mathematical expression corresponding to this diagram there is no difficulty at high energy. And for low energy the diagram gives practically the same as the original diagram (without W) provided this W is sufficiently heavy. A heavy W is something that will not move very much at low energies, and the effect is that the whole behaves then as if the W line is contracted to a point.

Well, that W has been found experimentally at CERN in 1983 (1984 Nobel prize to Rubbia and vander Meer). Its mass is considerable: it is 85 times heavier than the proton. You need a lot of energy to make such a particle. Its mass represents an energy equivalent to 80 GeV = 80,000 Mev (compare the electron mass, 0.5 MeV!). But in 1983 a machine was available that produced energy bubbles of about 900 GeV and that was enough. That is not immediately obvious, because the energy bubbles were produced colliding protons, and protons themselves tend to be somewhat extended objects. The energy was therefore not too well concentrated. Anyway, it worked, and since then we are sure about the existence of the vector-bosons.

Theoretically the existence of the W was guessed on the basis of the high energy behaviour of diagrams. That principle is really on the basis of the theory developed in the early seventies, and for which the 1999 Nobel prize was given ('t Hooft and V.). That theory goes a lot further, through the study of hypothetical processes and considering the high energy behaviour of such processes. Even if those reactions cannot be reproduced in the laboratory, the theory should never really produce idiotic behaviour as discussed above. So let us go on.

Here a generalization of the anti-particle idea must be introduced. The new rule is: given a vertex then also the vertex with all arrows reversed must exist. Thus in the figure the left diagram implies the existence of the one on the right.

The first process that we will consider is the scattering of a W from and electron. It is a hypothetical reaction, because there is no way that we can produce beams of

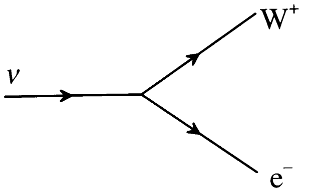


**Fig. 17.18**

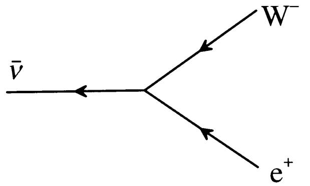


**Fig. 17.19**

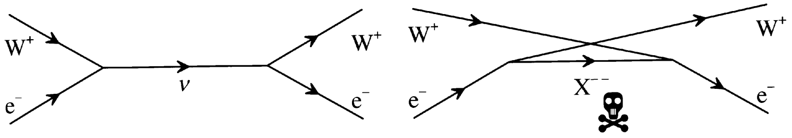


**Fig. 17.20**

vector-bosons. They are actually quite unstable, once produced they decay swiftly into lower mass particles.

Here are two diagrams for W-e scattering. We used for the left diagram only the $\nu$-W-e couplings (one of them completely crossed) that occur in the figures above. Thus the left diagram should exist. But its behaviour is bad at high energies. Peeking at the corresponding diagrams for photons and electrons, namely Compton scattering, we invented another diagram where a W is emitted before the incoming W is absorbed. Indeed, that would repair things, but unfortunately that would require a particle $X^{--}$ with a double negative charge. Nature is very strict about charge conservation, so starting with an electron and emitting a positively charged W requires that the third particle has a double negative charge. And that is bad, because there is no such particle.

Is there another solution? This requires some creative thinking, and the figure shows the solution. It involves a new particle that must be electrically neutral. It is called the $Z^0$, and we must ask the experimentalists if it exists.

The $Z^0$ was seen also by Rubbia and van der Meer, in the above mentioned 1983 experiment. Actually the nicest and cleanest way of producing such a $Z^0$ is through another reaction, obtained from the one abouve by crossing.

The reaction corresponding to this pictures,

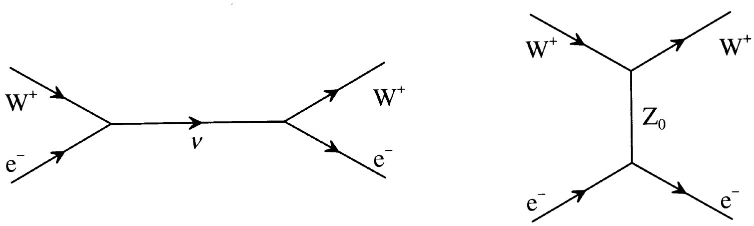


**Fig. 17.21**

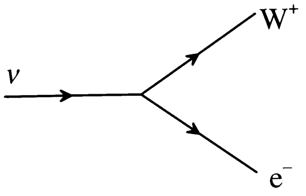


**Fig. 17.22**

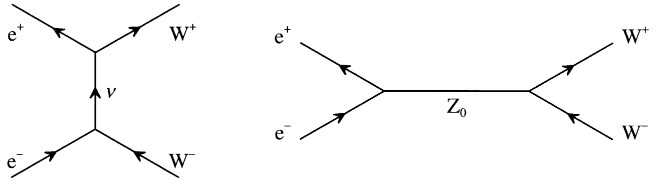


**Fig. 17.23**

$$e^- + e^+ \rightarrow W^+W^- \tag{17.4}$$

was observed at the largest machine available at CERN (called LEP, for Large Electron Positron collider), where 100 GeV electrons were collided with 100 GeV positrons. Many such events have been seen, and the $Z^0$ has been studied in great detail and with great precision. There is perfect agreement with the theory.

Let us summarize the rules that we have learned. Crossing. Moving for an existing process incoming lines to become outgoing and vice-versa produces new processes that must exist as well. This implies the existence of anti-particles. As mentioned before, the rule for anti-particles goes a little further: whenever there is some vertex also the vertex with all arrows reversed must also exist.

Good high energy behaviour. This requires that for any process, if there is one diagram of a type as shown below, at least one of the others must exist as well.

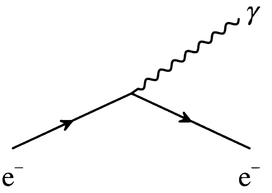


**Fig. 17.24**

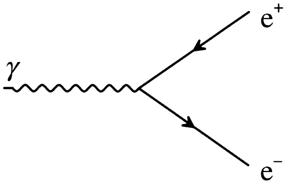


**Fig. 17.25**

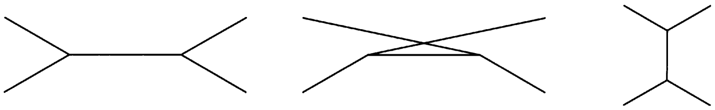


**Fig. 17.26**

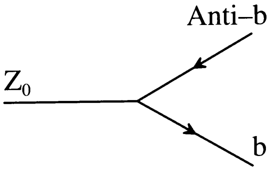


**Fig. 17.27**

## Top-Quark

Let us finally discuss how the top-quark came into the picture. At CERN when producing the $Z^0$ various decay modes were observed. Among them a decay mode of the $Z^0$ involving a new particle, called the bottom-quark. This was not the way the bottom-quark was originally discovered, it was first seen in another reaction. The bottom-quark has a mass of about 4.3 GeV and a fractional charge, namely $-\frac{1}{3}$.

Following by now familiar methods we consider $W^+$-bottom scattering. That is a purely hypothetical reaction, there is no way that we can produce a beam of vetorbosons (W's). Actually, there are some bottom-quarks present in protons and neutrons, so as a target we could use protons. That would still be difficult, because the amount of bottom-quarks in a proton is very small.

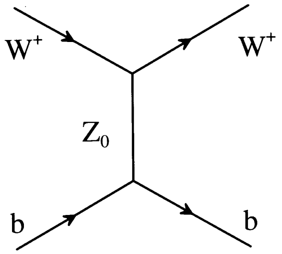


**Fig. 17.28**

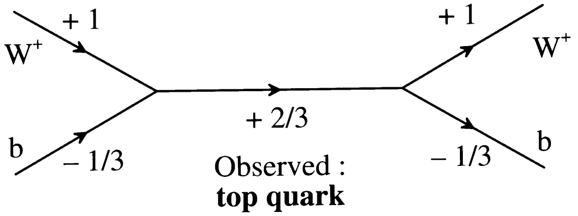
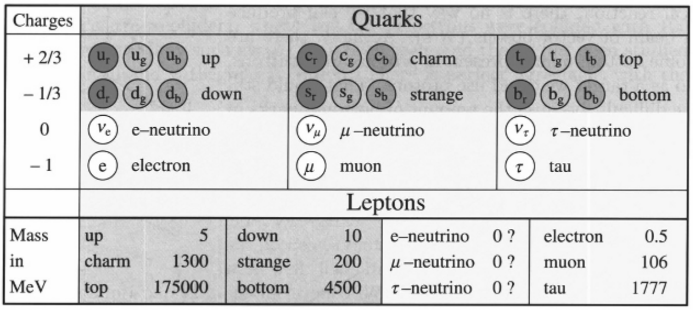


**Fig. 17.29**

The diagram shown must exist. However, that diagram by itself produces a bad result with respect to high energy behaviour, as discussed before. According to our rules there must exist some other diagram and there are two possibilities.

The first possibility is shown in the figure. It involves a new particle. We have indicated the electric charges, and from conservation of charge we deduce that this new particle must have a charge of $+\frac{2}{3}$. And indeed, such a particle has been observed at Fermilab near Chicago. It is called the top-quark. Before it was found the theoretical knowledge using precision results from LEP was perfected to the point that the mass of this top-quark could be predicted quite accurately. This of course greatly facilitated the experimental search for that particle. To be precise, the prediction for the top-quark mass was $177 \pm 7\,\mathrm{GeV}$, the value found at Fermilab is $174 \pm 5\,\mathrm{GeV}$. The fact that the theoretical prediction for the top mass agreed so well with the experimental result was quoted by the Nobel Committee on the occasion of the 1999 Nobel prize.

To be complete, there are some uncertainties related to another particle called the Higgs particle, whose existence can be deduced by considering $W^+ - W^+$ scattering. We will not discuss that here.



| Charges | Quarks | | |
|---|---|---|---|
| + 2/3 | $u_r$ $u_g$ $u_b$ up | $c_r$ $c_g$ $c_b$ charm | $t_r$ $t_g$ $t_b$ top |
| – 1/3 | $d_r$ $d_g$ $d_b$ down | $s_r$ $s_g$ $s_b$ strange | $b_r$ $b_g$ $b_b$ bottom |
| 0 | $\nu_e$ e–neutrino | $\nu_\mu$ $\mu$–neutrino | $\nu_\tau$ $\tau$–neutrino |
| – 1 | e electron | $\mu$ muon | $\tau$ tau |
| | Leptons | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mass | up | 5 | down | 10 | e–neutrino | 0 ? | electron | 0.5 |
| in | charm | 1300 | strange | 200 | $\mu$–neutrino | 0 ? | muon | 106 |
| MeV | top | 175000 | bottom | 4500 | $\tau$–neutrino | 0 ? | tau | 1777 |

**Fig. 17.30**

## Concluding Remarks

It will be obvious to the reader that this text only scratches the surface of the subject matter. One can do only so much in a note as short as this.

On the next page an overview of the known elementary particles is given. Matter around us is build up from electrons, protons and neutrons. The proton contains a down and two up quarks, the neutron an up and two down quarks. The quarks come in three kinds, coded using the colors red, green and blue. These quarks together with the electron and the electron-neutrino constitute the first family. There are however two more families, differing from the first mainly because the particles are much heavier. Otherwise they have the same properties. Nobody knows why there are three families.

The known particles and their names, masses and charges. Every ball corresponds to a particle. There are three families with largely identical properties. The particles with non-integer charge are called quarks, the last two in every family are called leptons. Every quark comes in three varieties, indicated by means of the colors red, green and blue. There is thus a red, green and blue charm quark, with a mass of 1300 MeV and with charge $\frac{2}{3}$. The neutrino's have possibly a very small mass, subject of further experimentation.

To each of these particles corresponds an anti-particle with the same mass, but with the opposite charge. For example, there is an anti-muon with charge +1 and an anti-$\tau$-neutrino with charge 0.

In addition there is the $W^+$ (charge +1, mass 80330 MeV), the $W^-$ ($-l$, mass 80330), the $Z^0$ (0, mass 91187), eight gluons $(0,0)$, the photon $(0,0)$ and the graviton $(0,0)$. The sofar hypothethical Higgs particle has a mass of at least 114000 MeV and charge 0.

**Fig. 17.31** Professor Martinus Veltman during the lecture at University of Tokyo (2003)