CHAPTER 6

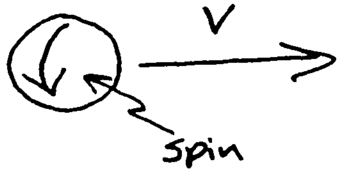
PARTICLES

One of the great enterprises of twentieth century physics is the search for the ultimate constituents of matter and the forces through which they interact. In this chapter we discuss fermions, the building blocks of matter. We shall describe the giant machines, particle accelerators, used to study these smallest bits of the Universe and ~~the~~ define the characteristics that distinguish one fermion from another. Then we shall describe each of the fermions individually. Finally, we shall consider "resonances" of the fermions and evidence that the known fermions might have internal components.

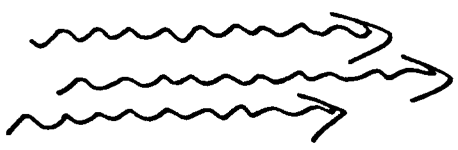
FERMIONS AND BOSONS

Nature employs two general classes of particles, fermions and <u>bosons</u>. Fermions are the structural units of matter -- the bricks in the grand edifice of the Universe -- and bosons transmit the forces through which they interact. We will discuss the bosons in detail in Chapter 7.

Fermions differ from bosons in spin: fermions carry spin quanta in odd multiples of 1/2 (1/2, 3/2, 5/2, etc.) while bosons carry integer spin (0, 1, 2, etc.). Fermions also differ from bosons in that they tend to avoid other fermions, while bosons aggregate happily in large numbers: fermions obey the Pauli exclusion principle (no two fermions can occupy the same energy state) while bosons obey Bose-Einstein statistics (indefinite numbers of bosons can occupy the same energy state).

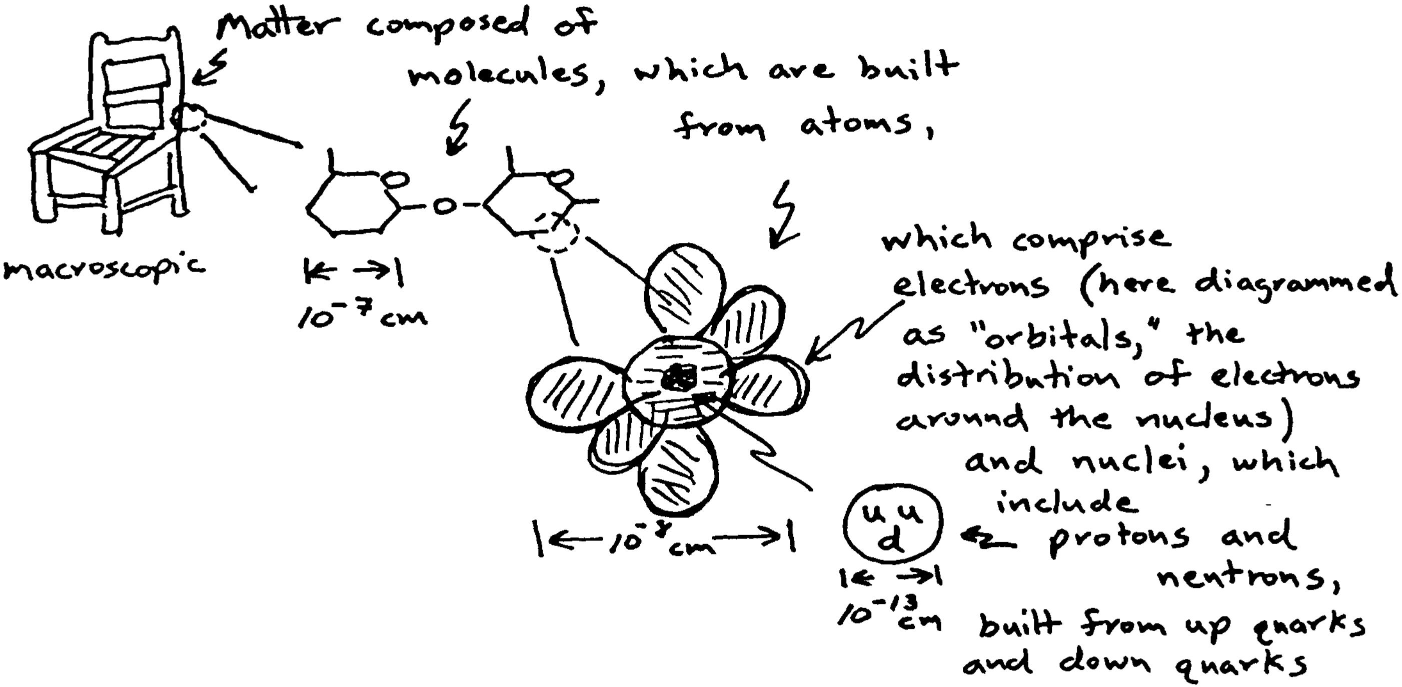


electron, a fermion, with angular momentum ½ along axis of motion

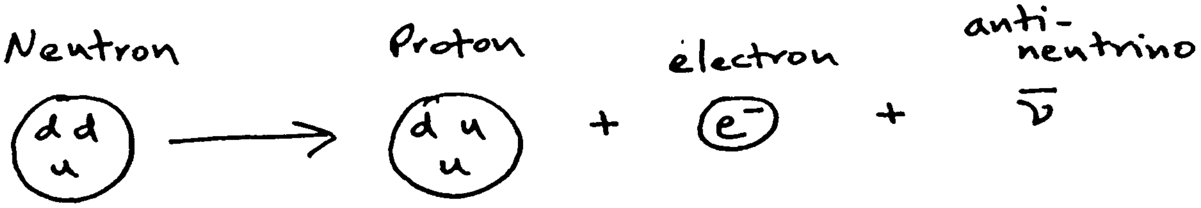


photons, e.g. in laser beam, all with spin 0, all with same energy

A plethora of particles pop out of accelerator experiments and cosmic ray showers, but all ordinary matter in the Universe is built from three fermions -- electrons, up quarks and down quarks. If we dissect matter, probing from large to small, we find that the objects around us -- trees, blackboards, clouds, people -- are built of molecules. Molecules are constructed of atoms, and atoms comprise <u>electrons</u> and nuclei. Nuclei, in turn, include protons and neutrons, which are made of <u>quarks</u>.



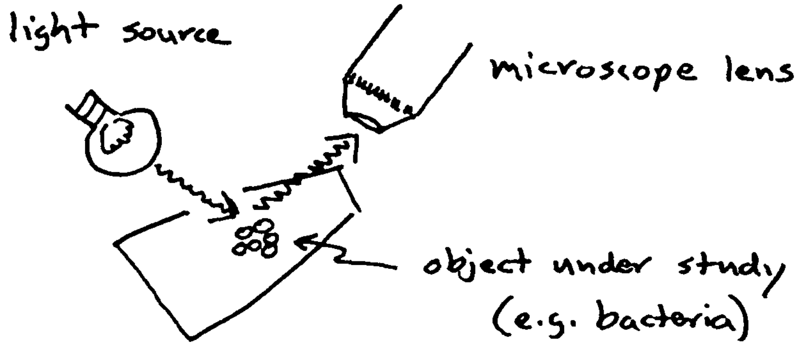
Besides electrons and quarks, the Universe is awash in neutrinos, the most abundant but most bashful of the fermions. There are primordial neutrinos, left over from the creation of the Universe, and neutrinos also appear as by-products of particle decay.



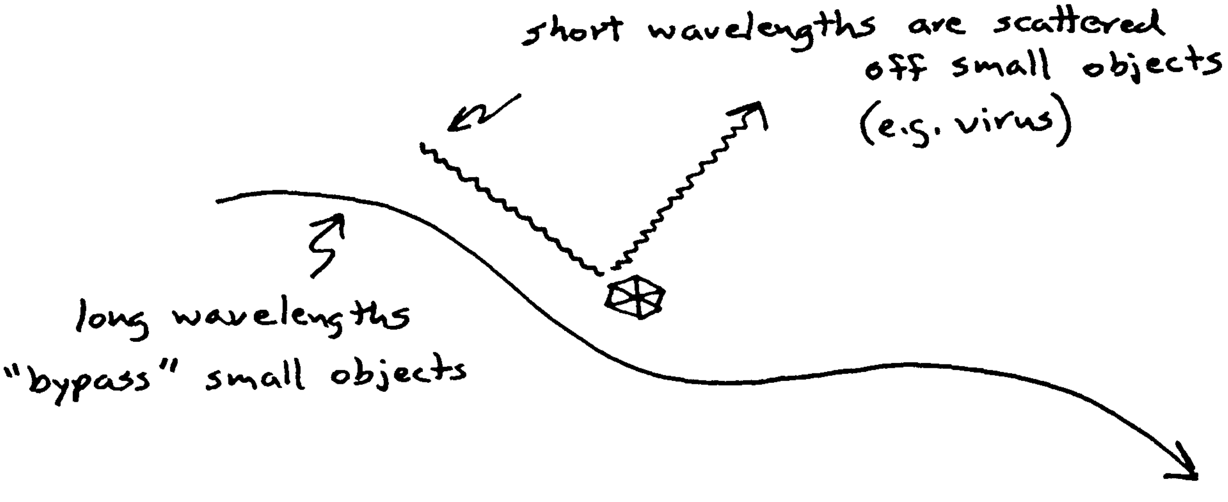
PARTICLE ACCELERATORS

Our knowledge of the particles comes primarily from experiments in particle accelerators, which function essentially as high-resolution microscopes allowing us to "see" inside atoms. To understand how accelerators work, we can compare them to the familiar light microscope.

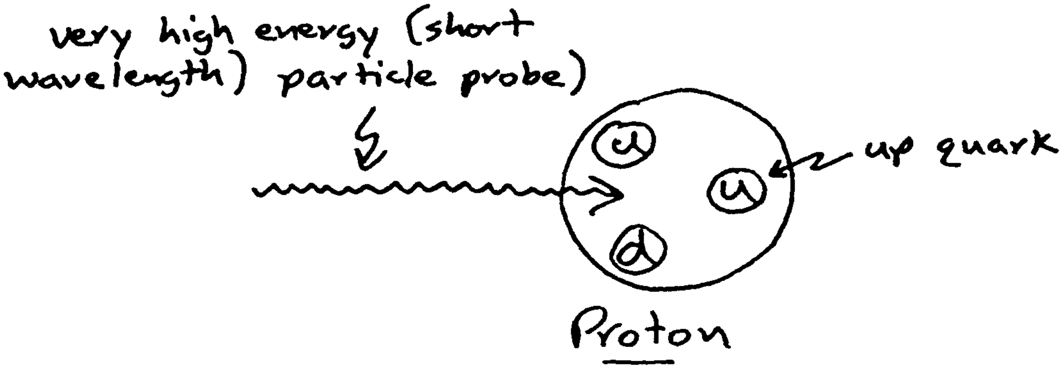
We see objects under a light microscope by reflecting light off them or refracting light through them.



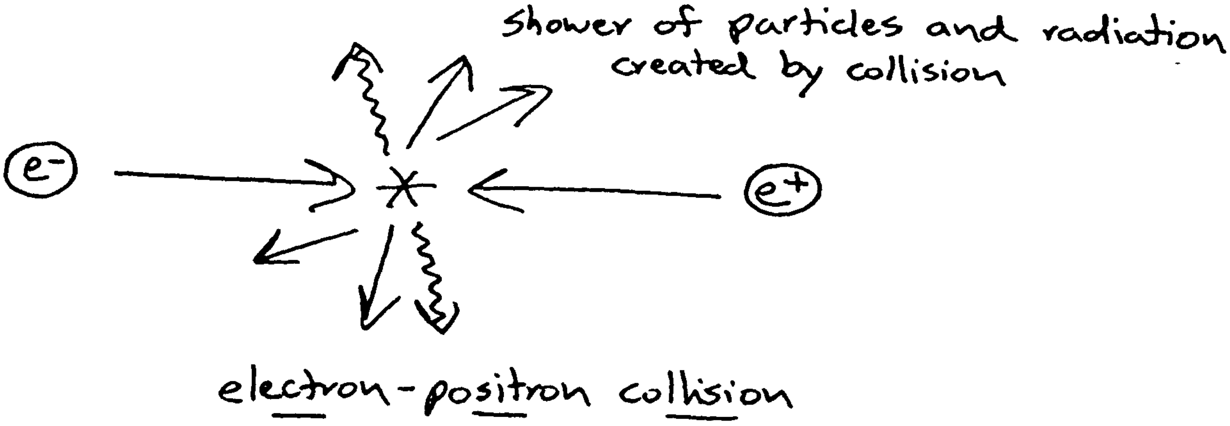
The resolution of a microscope -- the measure of the smallest object the microscope can discern -- is inversely proportional to the wavelength of the light used. At shorter wavelengths, we can see smaller objects.



Accelerators employ particles as probes instead of light. They pump charged particles to high energies, then focus them on a target. High energy corresponds to short wavelength (by $E = hf$), so the particle beam can probe dimensions smaller than an atomic nucleus. The most energetic accelerators can even probe inside the protons and neutrons.

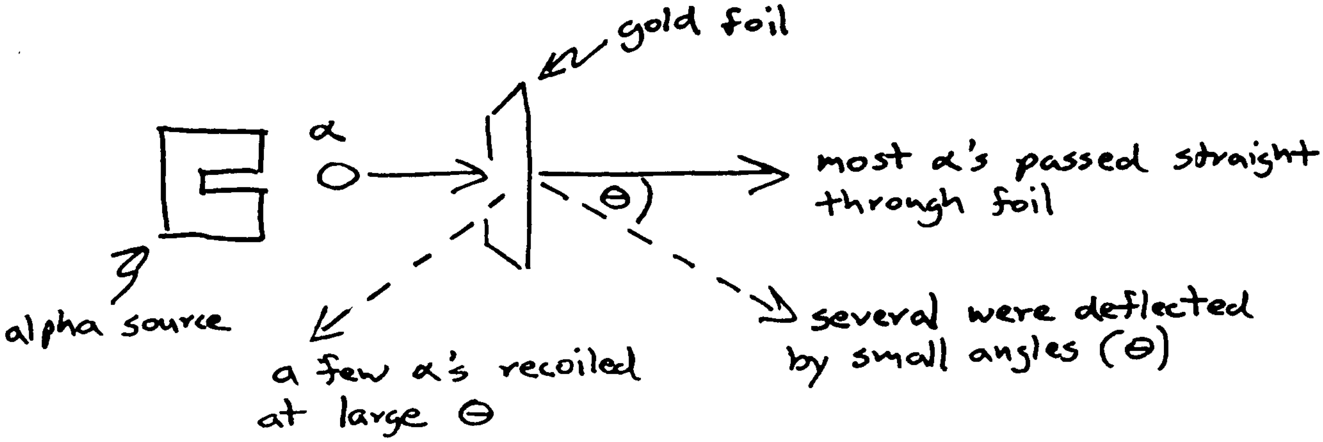


Collisions at high energies also create particles by converting beam energy into mass. Colliding beam accelerators, which accelerate beams of particles in opposite directions, are more efficient than fixed target machines in this process.



Of course, we do not see fermions directly inside the accelerators. Instead, sophisticated detectors measure particle characteristics in three general types of experiments -- scattering, spectroscopy, and particle breakup.

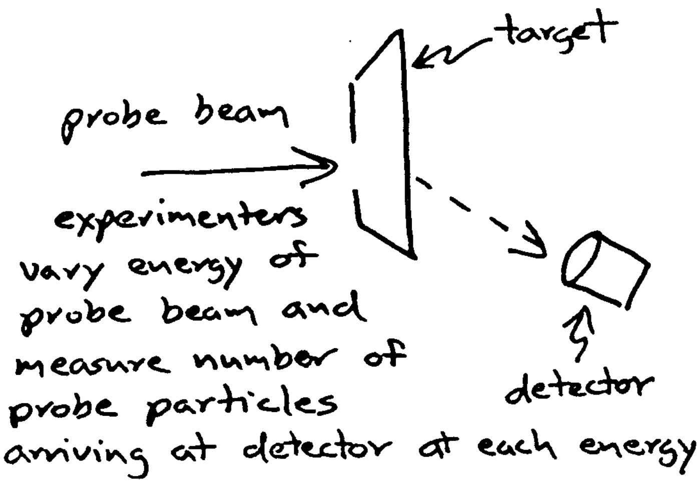
The classic scattering experiment, first performed in 1909, is Ernest Rutherford's detection of the atomic nucleus. Rutherford, Hans Geiger, and Ernest Marsden bombarded gold foil with alpha particles (helium nuclei) from a radioactive source and counted the alpha particles striking a scintillation counter at various angles from the incident alpha beam. They found that most alphas passed straight through the foil undeflected, but a few recoiled ("scattered") almost directly backward, as if they bounced off an immovable "brick wall."

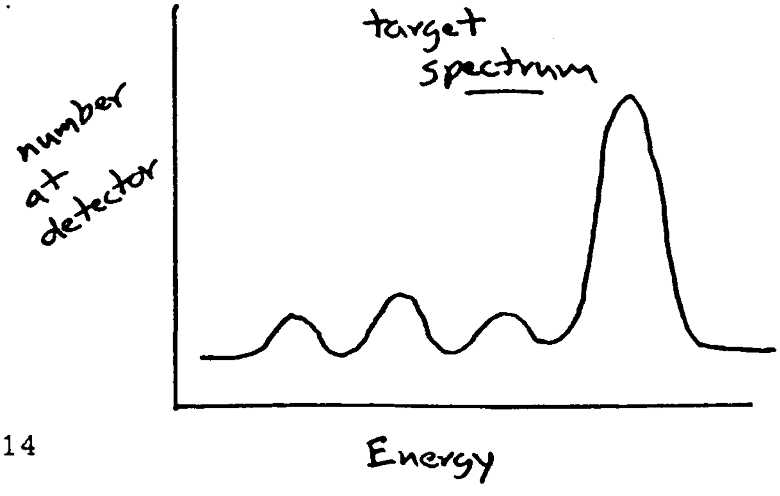


The experimenters concluded the gold atom is mostly empty space, but with a massive nucleus about 10^-12 cm in diameter, one ten-thousandth the diameter of the atom. Those alphas that graze the nucleus are deflected at shallow angles. Those that strike the nucleus head on bounce backward.

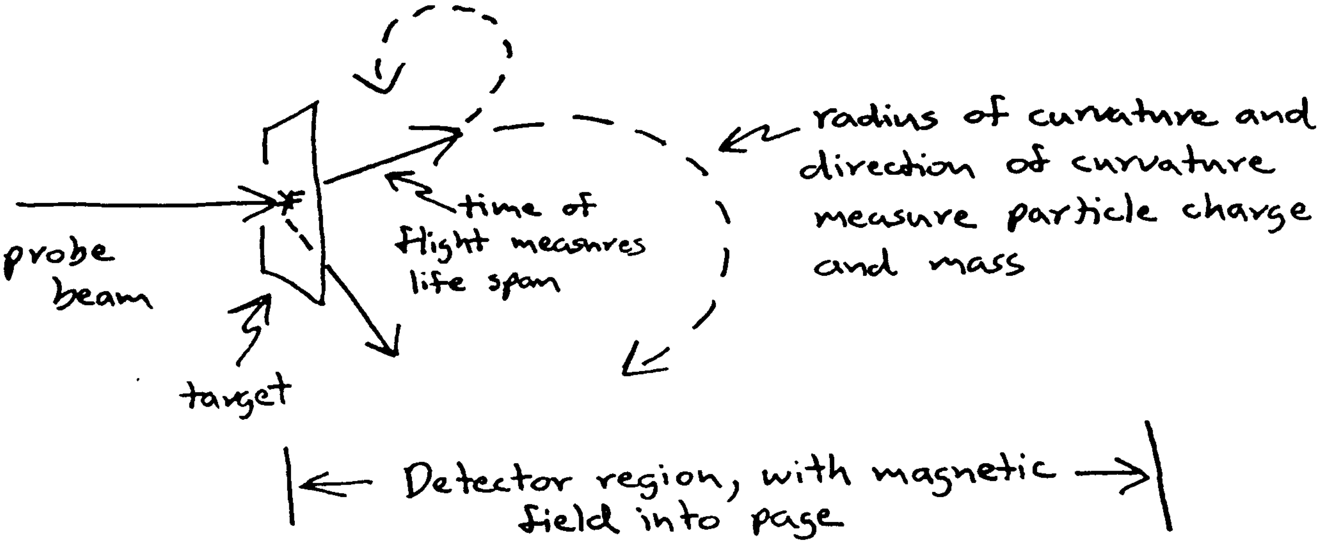
Similar scattering experiments, performed during the past thirty years, have probed even smaller dimensions, inside protons and neutrons.

Splectroscopy experiments bombard targets with particle beams over a range of energies and measure how much of the beam energy is absorbed by the target. The process duplicates absorption spectroscopy, described in Ch. 5, by which astronomers can study the chemical composition of gas clouds: each atomic element specific frequencies of light. So with nuclei, and so with individual particles: each nucleus and each fermion has its characteristic spectrum. The transition energies for nuclei are much higher than electron transitions in atoms, and the transition energies for particles are higher still.



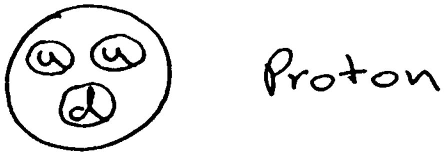


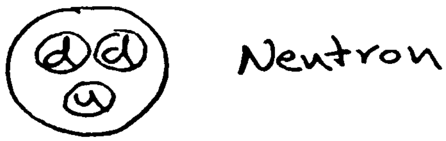
Breakup experiments supply enough energy in the probe beam to shatter the target. Various detectors, then, measure the masses, electric charge, life-times, etc., of the fragments.



CATALOGUING THE PARTICLES

Just as the number of protons in atomic nuclei defines the chemical elements (carbon has six protons, sodium eleven, etc.) so the particles produced in accelerators can be catalogued according to their constituent fermions. A proton, for instance, has two up quarks and a down quark, and a neutron has two down quarks and an up quark.





We catalogue the fermions, in turn, according to measurable characteristics such as mass, electric charge, spin, and the forces to which the particle responds. Each fermion has a unique fingerprint. An electron, for instance, carries a mass of 0.51 Mev, charge -1, spin 1/2, and it responds to the electromagnetic force, the weak force, and gravity. No other particle shares this exact combination of traits.

(There are a number of other characteristics, including "charm," "strangeness," "baryon number," and "lepton number," that can be measured and which physicists use to catalogue the particles. Such features are useful in cataloguing the more esoteric "resonances" (see below), but we shall limit ourselves to a consideration of the basic characters.)

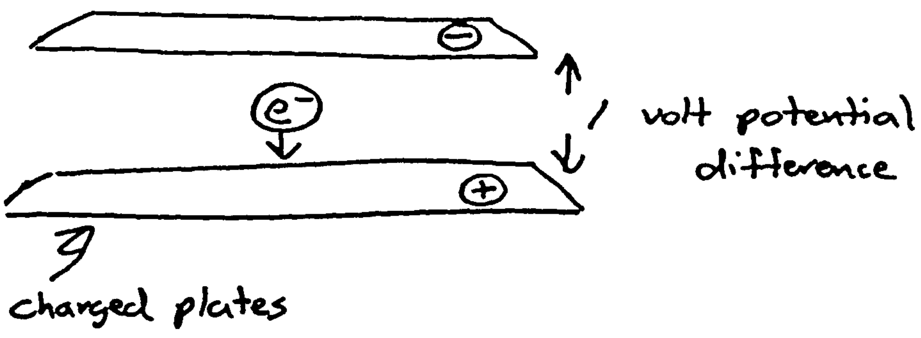
Fermions

LEPTONS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV/c^2)	ELECTRIC CHARGE
ELECTRON NEUTRINO	ν_e	ABOUT 0	0
ELECTRON	e or e^-	0.511	−1
MUON NEUTRINO	ν_μ	ABOUT 0	0
MUON	μ or μ^-	106 6	−1
TAU NEUTRINO	ν_τ	LESS THAN 164	0
TAU	τ or τ^-	1,784	−1

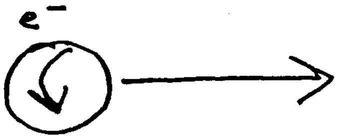
QUARKS			
PARTICLE NAME	SYMBOL	MASS AT REST (MeV/c^2)	ELECTRIC CHARGE
up quark	u	310	2/3
down quark	d	310	−1/3
charmed quark	c	1,500	2/3
strange quark	s	505	−1/3
top quark	t	> 22,500 HYPOTHETICAL PARTICLE	2/3
bottom quark	b	ABOUT 5,000	−1/3

from Quigg, *Sci. Am.* 4/85

Physicists measure mass in electron volts, which are units of energy. One electron volt represents the kinetic energy acquired by an electron falling through an electrical potential of one volt.

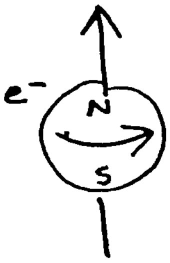


We can visualize "spin" by thinking of particles as spinning tops. Spin measures a particle's intrinsic angular momentum. It is quantized in units of $\hbar$, Planck's constant/2π. A fermion, which has spin 1/2 (i.e. spin $\hbar/2$), can spin in one of two directions, either clockwise or counter-clockwise, along the axis of its motion.



an electron with "right-handed" spin

Accelerators cannot count revolutions per minute, to measure spin directly, but the property was deduced to explain fermions' magnetic moment. Fermions respond to an external magnetic field as if they are magnetized, i.e. they behave as if they have a north pole and a south pole. This magnetization can be explained if the particles are spinning electric charges.

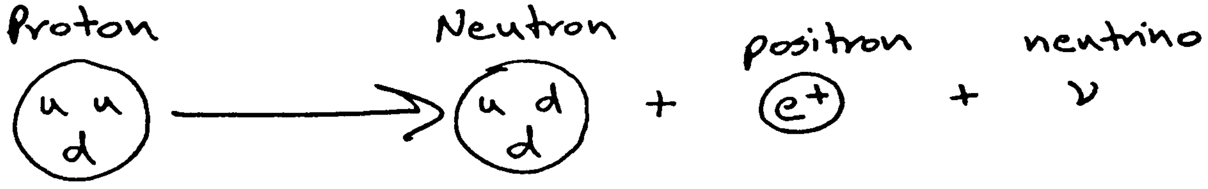


electron behaves like a tiny magnet

Spin also explains the distribution of electrons in atoms. No two fermions can occupy the same state (the Pauli exclusion principle), but electrons distribute themselves in <u>pairs</u> in the different energy levels around an atomic nucleus. This is possible if the members of the pair have opposite spin states.

ANTI-PARTICLES

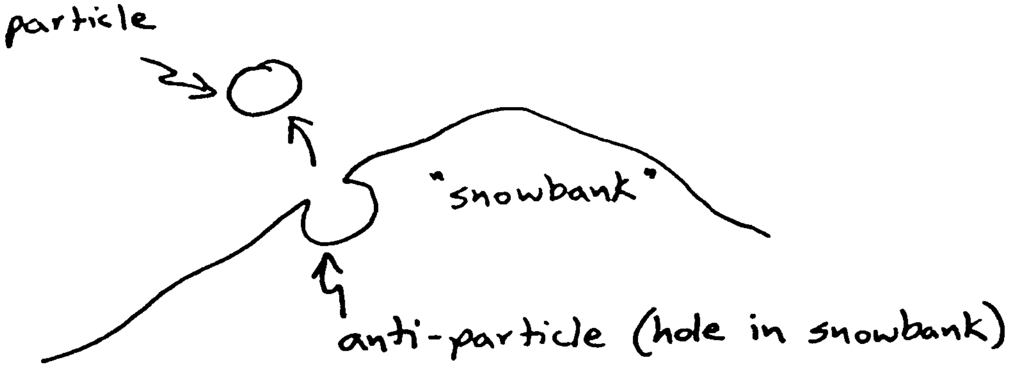
Anti-particles are produced in high-energy accelerator events, in cosmic ray interactions (high energy particles from outer space), and in particle decay. (For instance, proton beta decay releases a positron and a neutrino, and neutron decay releases an electron and an anti-neutrino.)



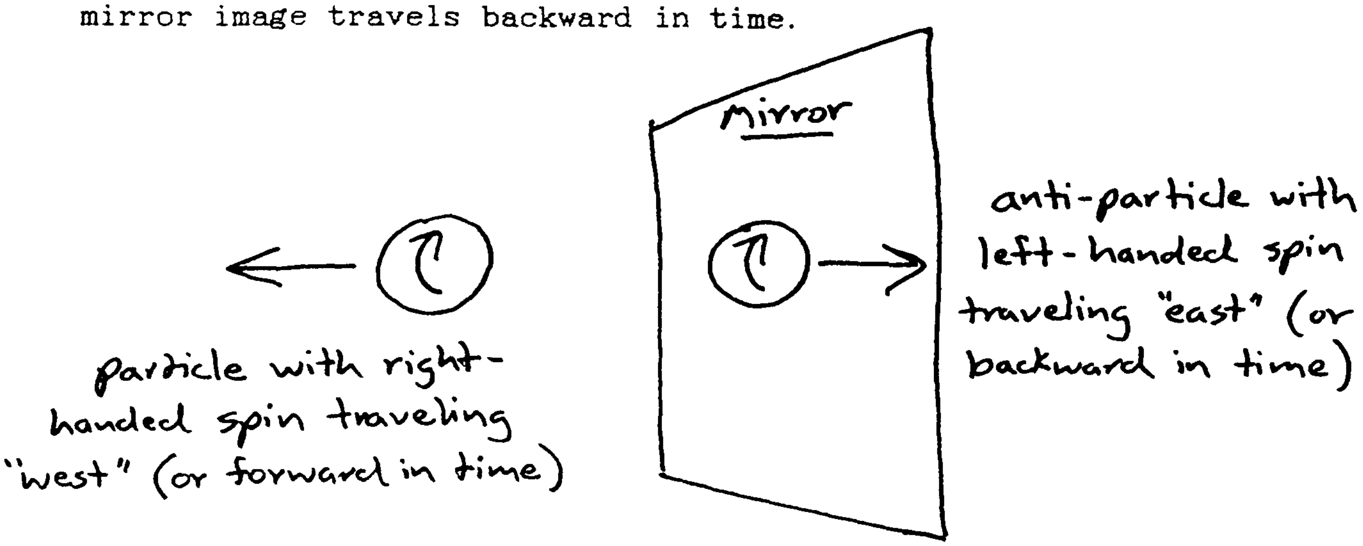
positron is an anti-electron

Anti-particles carry mass and spin equivalent to their brother particles but have just the opposite electric charge. For instance, a positron, the anti-particle to the electron, carries the same mass and quantum of spin as an electron but has a charge of +1. When a particle meets its anti-particle, the two annihilate and release energy equivalent to their combined mass energies plus their kinetic energies. Since particles vastlly outnumber anti-particles in our Universe, anti-particles don't survive very long.

One way of visualizing the relationship between particles and anti-particles is to think of spacetime as a snowbank and particles as products of the snowbank: Anti-particles are holes left in the snowbank after the particles (snowballs) have been removed. Pulling a particle out of the snowbank -- creating a particle/anti-particle pair -- requires energy, and when a particle falls back into the hole (particle meets anti-particle) it releases that energy.



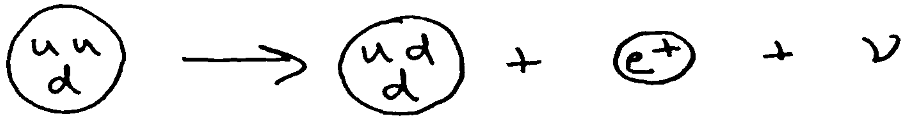
Alternatively, we can model anti-particles as mirror-images of the particles. Mathematically, if a particle appears to be "right-handed," its anti-particle is "left-handed," and where a particle travels forward in time, its mirror image travels backward in time.



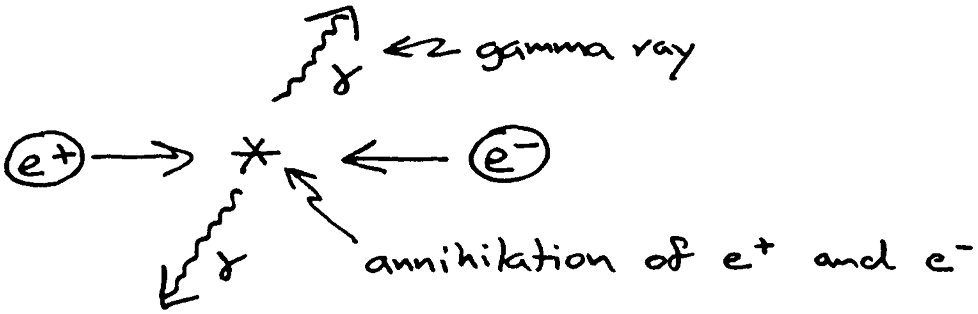
POSITRON EMISSION TOMOGRAPHY

Medical scientists exploit anti-particles to study anatomic structure and physiologic function inside the body. Positron emission tomography (PET for short) provides an unprecedented tool for research and diagnosis.

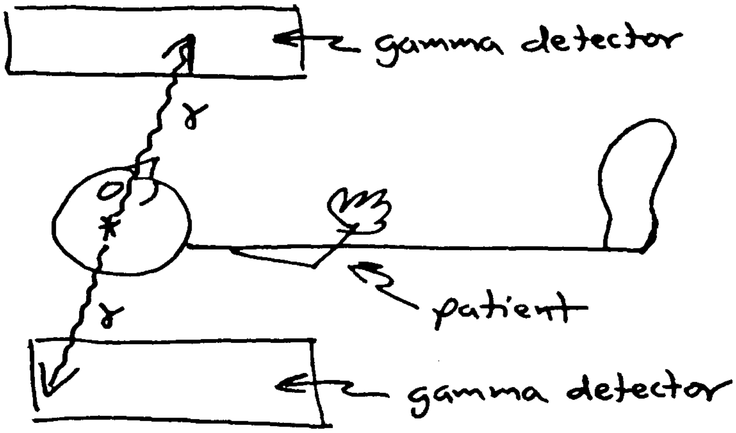
In PET, a patient drinks a solution containing carbon 11, that is carbon with six protons but only five neutrons, instead of the usual six, in its nucleus. To study the brain, for example, a patient drinks glucose incorporating carbon 11. The carbon 11 nucleus is unstable (too much repulsive electric charge in relation to the "glue" binding nucleons inside the nucleus) and is prone to beta decay: a proton in C11 decays to a neutron, a positron, and a neutrino.



The positron very quickly annihilates with one of carbon's electrons, producing a pair of gamma rays which emerge in opposite directions.



Gamma detectors outside the patient's body record the gamma rays. Knowing that simultaneous rays emerged from the same point, it's possible to determine where in the body they originated. By recording such gamma ray pairs, it's possible to create a detailed image of the tissue of origin.



Positron emission tomography is especially useful because it enables scientists to image not only internal structures but physiologic <u>processes</u> as well. For example, if a patient listens to music during a PET scan, a particular region of the brain -- the auditory center -- "lights up" (i.e. concentrates the C11/glucose and therefore emits more gamma rays). When the patient <u>analyzes</u> the music ("4/4 time, D major, allegro") another region of the brain lights up. We can "watch" the brain at work.

LEPTONS: ELECTRONS AND NEUTRINOS

Fermions such as electrons, positrons, and neutrinos that respond to the weak force but not the strong force, are called leptons, or the "light ones."

We are familiar with electrons: they produce sparks when we drag our feet across a carpet, and the flow of electrons powers our electric appliances. Electrons are the most thoroughly studied of all the elementary particles: as described in previous chapters, electrons were the first fermions to be weighed and measured. Electrons in diffraction experiments demonstrate the wave nature of particles. Electrons recoiling in photoelectric experiments reveal the quantum nature of light, and electron transitions in atoms demonstrate the quantum nature of energy. Physicists routinely use electrons to probe the structure of other particles.

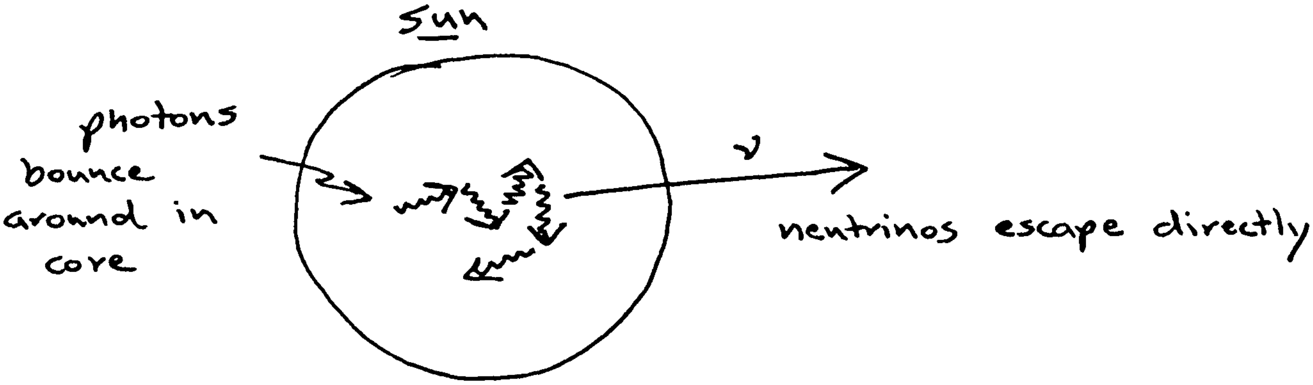
Neutrinos are the most common fermions in the Universe -- and also the most elusive. They outnumber electrons and protons by about ten billion to one, but they interact so rarely with other particles that they can pass through masses such as the Earth or even the sun with little chance of interaction, i.e. without bumping into anything. Neutrinos are essentially pure spin: they carry no electric charge, and they are thought to be massless (but see below).

Neutrinos interact rarely with other particles because they respond only to the weak force and the force of gravity. The force of gravity is insignificant at the scale of individual particles because particles have such little mass, and the range of the weak force is exceedingly short: in order to feel the weak force from another fermion, a neutrino must pass within 10^-16 cm --about one-thousandth the diameter of a proton. Such close approaches are very rare.

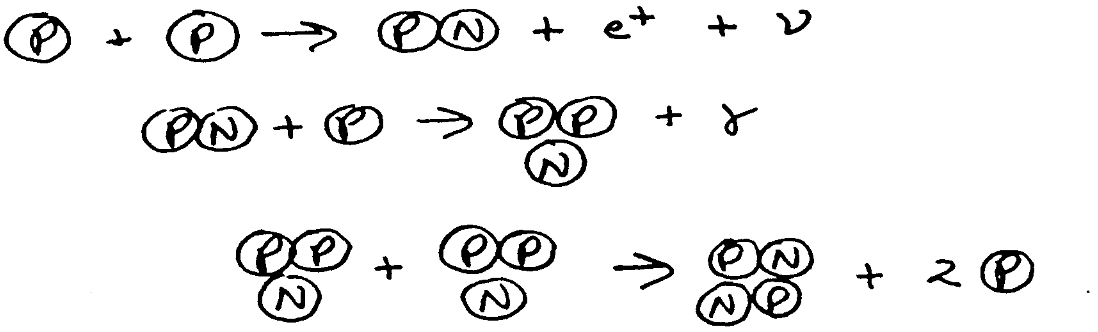
Despite the neutrino's shyness, physicists have constructed neutrino "telescopes" to study their behavior. Neutrino detectors incorporate vast pools -- hundreds of cubic meters -- of water or carbon tetrachloride (a cleaning solution). Of the billions of neutrinos passing through the volume of fluid, one does occasionally interact with a proton in the pool, and the reaction produces a detectable flash of light.

NEUTRINOS AS WINDOWS ON THE SUN AND UNIVERSE

Unlike neutrinos, photons respond to the electromagnetic force (in fact they are carriers of that force), which has infinite range, and therefore interact with charged particles inside the sun. Since the core abounds with free electrons and protons photons ricochet around the core for a million years, on average, while neturinos escape directly. Neutrino detectors, ~~then~~, tell us what happened in the core of the sun 8 and 1/2 minutes ago (the light-travel time from sun to earth), while sunlight is about a million years old.



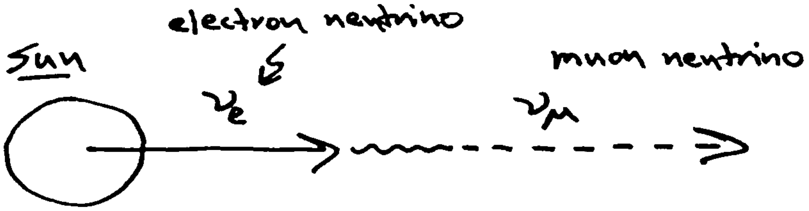
An intriguing problem in astrophysics is that of the "missing solar neutrinos". Solar physicists thought they understood the nuclear reactions at the core of the sun, reactions which produce neutrinos.



The "proton-proton" reaction, which produces neutrinos and gamma rays in the core of the sun

But when sophisticated neutrino detectors began counting solar neutrino flux (the numbers of neutrinos arriving at Earth), they found only about a third the expected number. Where are the "missing neutrinos"? Is the sun burning out? (We could still be bathed in the "old" photons of a once hotter sun.)

Recent theoretical study suggests that electron neutrinos might metamorphose en route from the core and become muon neutrinos (see below). Current detectors are not sensitive to the muon neutrinos. Other evidence suggests neutrinos may be trapped inside the core by the sun's magnetic field.



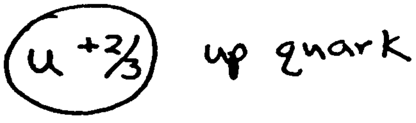
Physicists are intrigued by neutrinos for another reason. Neutrinos have been regarded as massless, but there is some evidence they may carry a small mass, on the order 10 eV. Even though this is vanishingly small, there are so many neutrinos that the total contribution may be enough to "close" the Universe. That is, neutrinos may contribute enough mass to stop and then reverse the expansion of the Universe. (We shall discuss this "missing mass" problem in more detail in Ch. 9.)

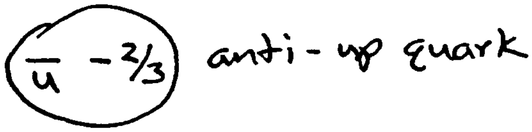
QUARKS AND HADRONS

Quarks are the fundamental constituents of nuclear particles (e.g. the proton and the neutron). In the Universe at large, there are two "flavors" of quark -- up and down.

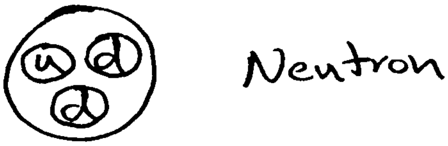
(The term "flavor" is whimsical. Particles do not actually taste like chocolate or vanilla: physicists use the term to express characteristics that are otherwise indescribable in ordinary language.)

Quarks carry fractional electric charge -- +2/3 (up quark) or -1/3 (down quark). Antiquarks carry the opposite charge -- +1/3 (anti-down) or -2/3 (anti-up).



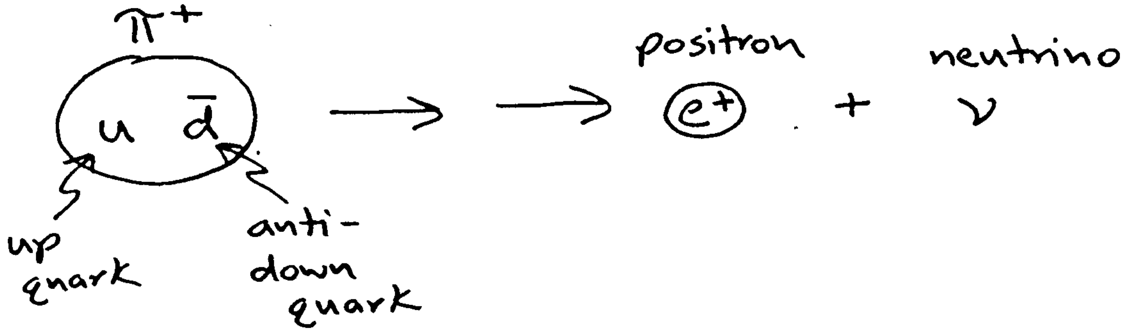


In nature, quarks always combine to form composite particles called hadrons, with net integer electric charge. There are two sub-categories of hadron, baryons and mesons. Baryons contain three quarks, and the mesons contain two quarks -- a quark and an anti-quark. The most common baryons are the neutron and the proton.



Pions are the most common mesons. They act as a kind of nuclear glue, and they appear in abundance in the decay products of cosmic rays and in the accelerators. It is interesting to note that mesons decay to leptons -- electrons, positrons, and neutrinos -- a hint that quarks are related to leptons.

Decay of the positive pi meson

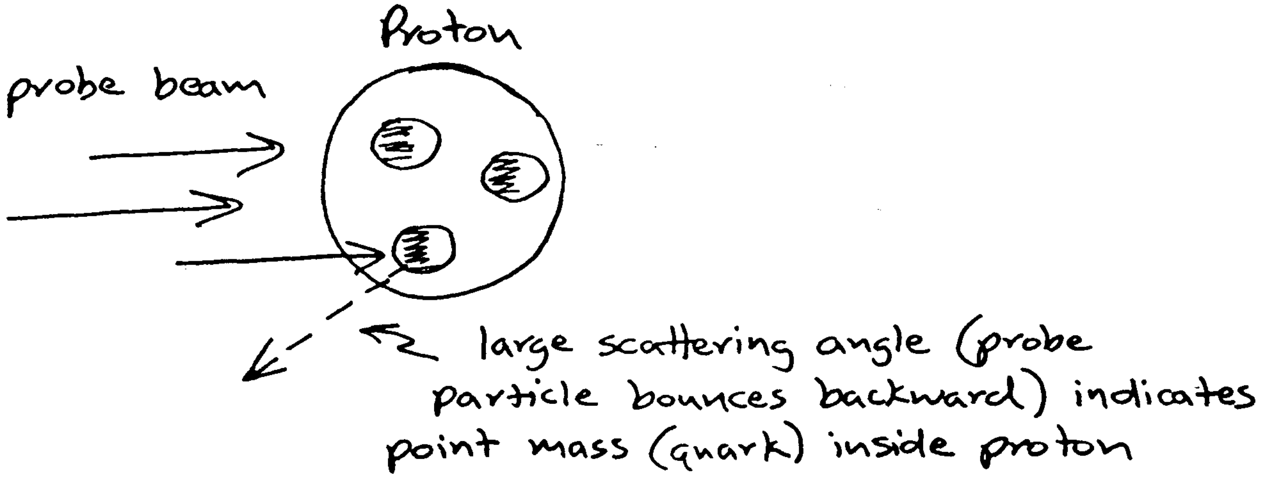


Experiments at Stanford University and elsewhere may have detected fractional charges characteristic of free quarks, but theory predicts quarks are permanently confined in hadrons: they cannot be pried out of baryons or mesons except at extreme temperatures, high above the energies ordinarily available in our Universe.

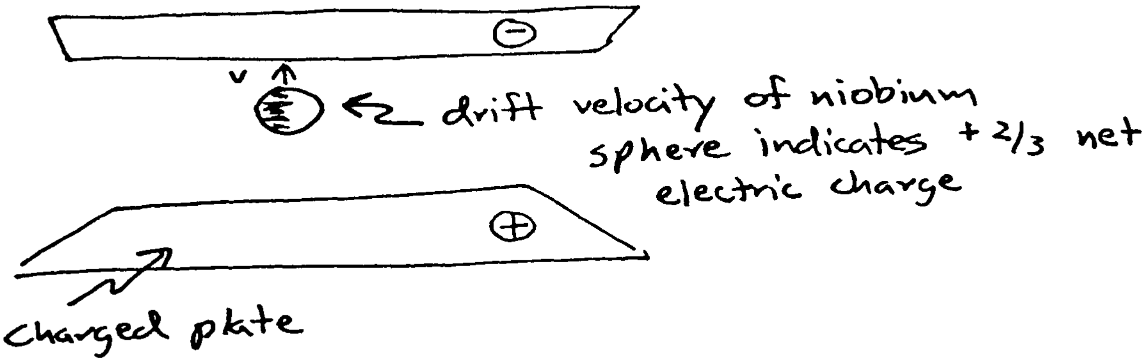
EVIDENCE OF QUARKS

If quarks are bound permanently inside hadrons, how do we know they exist?

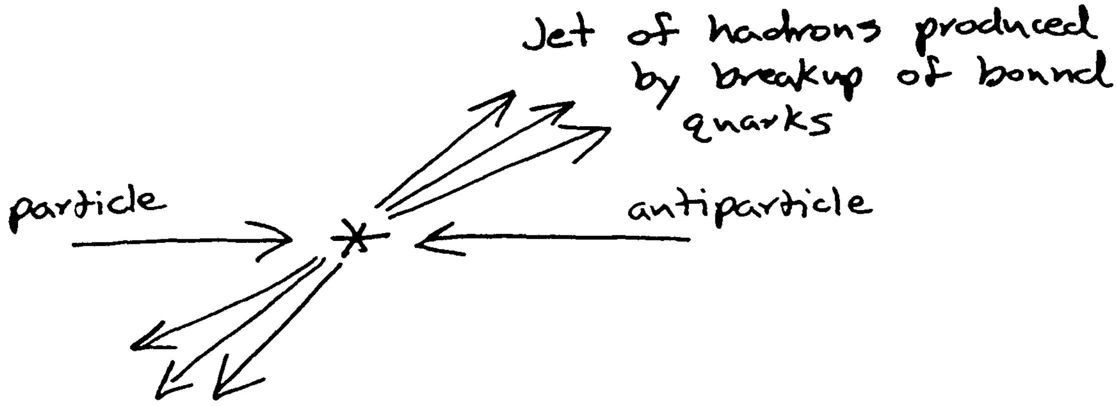
Three sets of experiments provide evidence of quarks. Repeating Rutherford's classic protocol, but operating at much higher energies and using electrons as probes, physicists find point masses embedded inside protons and neutrons. Those point masses carry charge and spin characteristic of quarks.



Stanford experimenters claim to have detected fractional charges directly by a method similar to Millikan's oil drop experiment. They suspended niobium spheres in an electric field and measured their net charge. Rarely (so rarely that the results remain controversial) they found net excess charges of -1/3 or +2/3.



A third experimental observation, particle jets, also supports the quark model. Jets are produced in high energy particle/anti-particle collisions. They are tightly collimated, two jets in opposite directions, at energies indicating they must result from the production of quark/anti-quark pairs.



HIGHER ENERGY FERMION FAMILIES

Included in the debris of high-energy accelerator and cosmic ray events are so-called "resonances" -- fermions with characteristics similar to the basic eight fermions (electron, neutrino, up quark, down quark, and the anti-particles of these four) but with greater mass. For example, a negative muon, μ^- (which we discussed as an example of time dilation in special relativity) is identical to an electron, except it has about 200 times the electron's mass. (The μ has the same charge, same spin, and reacts to the same forces as the electron.) More massive still is the tauon, τ^-, about 1800 times the electron's mass. Otherwise the τ^-, too, is identical to the electron.

The μ and τ are unstable, and both decay very rapidly to electrons and neutrinos. Hence the term "resonances:" they behave like higher frequency harmonics of the stable electron, just as a piano string may vibrate at a "fundamental" frequency and at higher harmonic frequencies.

Recent evidence suggests there are at most three families of fermions -- the basic eight fermions in one family plus two families of resonances.

Family 1	e^-	ν_e	u	d
	e^+	$\bar{\nu}_e$	$\bar{u}$	$\bar{d}$
Family 2	μ^-	ν_μ	c	s
	μ^+	$\bar{\nu}_\mu$	$\bar{c}$	$\bar{s}$
Family 3	τ^-	ν_τ	t	b
	τ^+	$\bar{\nu}_\tau$	$\bar{t}$	$\bar{b}$

(See table on p.116 for details.)

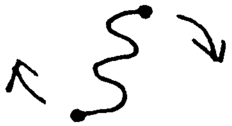
NEW MODELS OF FERMION STRUCTURE

Are the known leptons and quarks really fundamental particles, or are they composites themselves, built from smaller components? Here and there are intriguing hints that the quarks are related to leptons: mesons (built from quarks) decay to leptons, and when a neutron decays, one of its down quarks becomes an up quark plus leptons. If leptons and quarks can be inter-converted, it seems plausible they are just mixtures of the same underlying components.

Recent experimental data suggest the electron may have internal structure (Dehmelt, Science, 2/2/90): the magnetic moment of the electron departs from the magnetic moment predicted for a point particle -- i.e. there is evidence for a spatial distribution of electric charge within the electron.

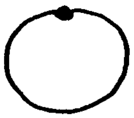
Measured magnetic moment of e^- is greater than magnetic moment calculated for - point charge

The current favorite candidate to explain the interrelation of fermions is string theory, which models particles as one-dimensional string segments rather than as point masses. String theory models the basic 8 quarks and leptons as straight, non-rotating segments, and the resonances (e.g. tauons and muons) are vibrating or rotating strings.



According to string theory, the forces governing particle interaction are carried at the string ends. String segments can interact end to end or in loops. As we shall see in the next chapters, such configurations may model forces more elegantly than do other theories.

An extension of string theory is the so-called "heterotic string." According to hetorotic string theory, fermions and bosons are all closed loops, and they are distinguished from each other by the frequency of vibrations around the loop. Heterotic string theory is especially attractive because it includes the force of gravity as a fundamental component: the basic closed loop is the graviton, the hypothetical quantum of the gravitational force. (See Ch. 7.)



graviton

heterotic string model of electron (vibrations around basic graviton loop)

We can't resolve string structure in our accelerators because they are so small (on the order 10^-39 cm) that they appear point-like.

Of the current attempts at unified field theories heterotic strings seem the most likely to encompass all the known particles and forces. Heterotic strings may be the fundamental "stuff" of the Universe.

SUMMARY

Physicists define two basic classes of particles: fermions and the bosons. Fermions are the building-blocks of matter -- the constituents of atoms -- while bosons carry the forces that hold those building-blocks together.

There are eight fundamental fermions: the electron and the anti-electron (positron), the electron neutrino and the anti-neutrino, the up quark and the anti-up, and the down quark and the anti-down. These eight build all known matter in the Universe. Other esoteric particles (resonances) are produced in particle accelerators and high energy cosmic ray interactions, but they decay quickly to the fundamental eight.

Leptons, including the electron and the neutrino, respond to the electromagnetic and weak forces but not to the strong force. Hadrons are particles composed of quarks, and they respond to all the forces, including the strong force.

New theories postulate more fundamental particles underlying the structure of leptons and quarks. Among the new theoretical models, string theory may encompass all the known fermions and forces in one elegant theoretical framework.

CHAPTER 6 QUESTIONS
PARTICLES

1. Distinguish fermions from bosons, and briefly describe their roles.

2. Diagram the component structure of a hydrogen atom. Identify the fundamental fermions that build the atom.

3. Suppose a group of physicists wanted to study the Z particle (a boson that carries the weak nuclear force). The Z has a mass of about 93 GeV (93 billion electron volts). If the research group is using an electron/positron collider for the study, how much energy must they invest in the colliding particles in order to create a Z? Assume all the kinetic energy of the colliding particles and all their mass is converted into Z's. The mass of the electron is about 0.511 MeV (0.511 million electron volts).

4. Suppose an accelerator accelerates electrons to 1 TeV (10^12 electron volts). What is the resolution of the particle beam (i.e., what is the diameter of the smallest structure that can be detected by the beam)?

5. Diagram the essential structure of a particle accelerator.

6. The following graph illustrates a method of determining the mass of a particle, in this case the Z. The researchers gradually increase the energies of electrons and positrons counter-rotating around an accelerator and count the number of Z's produced at each energy.

From the above data, what is the mass of the Z? Why is there a broad hump on the graph instead of a sharp peak?

7. Describe how it is possible to measure particle spin.

8. Define "electron volt," and explain why it is a measure of energy. Why is it also a measure of mass?

9. In what ways are anti-particles similar to their partner particles? In what way do they differ?

10. Explain the process by which anti-particles are produced in positron emission tomography, and explain how particle/anti-particle annihilation can be exploited to create an image of internal bodily structures.

11. Suppose the following event is observed: a neutron which was initially at rest decays. The decay products detected in a cloud chamber include a proton and an electron, and the net momentum of the decay products is as shown in the diagram. Assuming that momentum is always conserved, is it possible that the proton and electron are the only decay products? What can you say about the momentum, mass, and electric charge of any "missing" decay products?

12. Explain why photons take so long to escape from the core of the sun, while neutrinos escape directly.

13. How is it possible to detect neutrinos?

14. Why may neutrinos hold the key to the fate of the Universe?

15. Knowing the constituent quarks in a neutron, show that the neutron has a net 0 electric charge.

16. Cite experimental evidence for the existence of quarks.

17. In what ways is the muon similar to an electron? How does it differ?

18. What accelerator energies would be required to resolve a string 10^-39 cm. in diameter?

DEMONSTRATIONS
CHAPTER 6

1. <u>Particle tracks in a cloud chamber:</u>

Simple cloud chamber apparatus (clear plastic container lined with black construction paper, isopropyl alcohol, and a low-energy alpha source such as lead 210) is available from scientific suppliers such as Cenco. Soak the construction paper in alcohol and seal the container at room temperature, to allow air in the chamber to saturate with alcohol vapor. After two or three minutes, set the chamber on dry ice or on a container filled with liquid nitrogen. (A styrofoam cup cut to 1 cm. depth works well.) It helps to pack dry ice around the base of the chamber, or surround the chamber and liquid nitrogen container with insulating material. (I use the wax blocks from a ripple tank.) If using liquid nitrogen, be careful not to expose the plastic chamber directly to the nitrogen or the chamber will crack.

After one or two minutes of cooling, you will start to see pencil-line streaks of vapor emanating from the radioactive source. These are particle tracks. If you don't see tracks after a couple minutes, wipe any condensation off the source and try again.

Try embedding the chamber in a strong external magnetic field, e.g. between the poles of a large horseshoe magnet or between electromagnet coils. What happens to the particle tracks, and why?

Occasionally you will observe tracks that do not originate from the source but cross the chamber at odd angles relative to the source. What is the origin of these tracks?

2. Measuring the mass of the electron:

For this experiment you will need more sophisticated apparatus which is rather expensive and may not be readily available. A vacuum tube with a pinhole mask above the cathode is centered between two electromagnetic coils. Before turning on the electromagnetic, adjust the voltages in the tube to obtain a pencil-line electron beam directed straight up in the tube. Now adjust the magnetic field to curve the electron beam to a measurable radius in the tube.

Knowing the strength of the magnetic field, the electric charge on the electron, the accelerating voltage in the tube, and the radius of curvature, can you determine the mass of the electron? From the data you collect, what is your estimate of the electron mass?

3. Modelling the effect of mass on path curvature:

Construct a slant board with a spring-loaded launcher (such as from a pinball machine) directed at a fixed angle on the board. Launch spheres of various masses (e.g. marbles, steel bearings, lead bearings, wood spheres) at the same initial velocity across the board. What is the effect of mass on the curvature of the trajectory?

How can you be sure you are launching the different masses at the same initial velocity? (Hint: remember Newton's second law and the force exerted by a spring, F = kx, where k is the spring constant and x is the distance the spring is compressed from its rest position.)

4. Spinning charge produces a magnetic field:

Charge a light metal gyroscope using a Van de Graf generator or static electricity apparatus. Hang the gyroscope between the poles of a strong horseshoe magnet or electromagnet coils. Note its position before spinning the gyroscope. Now spin the gyroscope and note its position. What change do you observe, and why?

5. Dependence of resolution on wavelength:

Set up a ripple tank with slit about 2 cm. wide in a barrier at mid-tank. Vary the wavelength of waves traversing the slit (by varying the frequency of the wave generator).

Imagine you are trying to determine the diameter of the slit using only the apparatus available in the ripple tank. Which gives you more accurate information about the slit width, long wavelengths or short? Why?

6. <u>Model of a scattering experiment:</u>

Arrange heavy metal bearings or cylindrical weights on a flat surface, and shoot light marbles toward them. Place the "target" masses apart from each other at least twice the diameter of the "probe" marbles. What is the distribution of marbles scattering off the targets?

Try other targets, such as a bean bag, or targets with lighter masses and note the variation in distribution of probes and target particles after their collisions.

Have a friend distribute targets in a "black box," the insides of which you can't see but into which you can shoot probe marbles. Try to determine the contents and distribution of targets in the black box by the trajectories of the probe particles.

7. Resonance:

Release the damper on a piano. Stand near the strings and sounding board and shout a vowel (e.g. "oh"). Study the strings to try to determine which are vibrating, which are at rest.

Shout another vowel (e.g. "i"), and analyze the strings. How does the pattern of string vibration compare with the pattern of the initial vowel?

8. Resonance:

Have a friend place several different tuning forks in a "black box," the insides of which you can't see, or behind a barrier. Strike the tuning forks from a secon set to determine which forks are present in the "black box." What do you expect will occur if you strike a "probe" fork of the same frequency as one in the box?

9. Strings:

A number of factors affect the behavior of the hypothetical strings of particle physicists' imaginations. One factor is tension.

Determine how tension affects the fundamental frequency of a string by stretching a spring (such as a slinky) from a fixed point, or with the help of a friend. Count the fundamental frequency with the spring held relatively loosely. (At the fundamental frequency there is a half-wave between your hand and the fixed point at any time, and the half-wave oscillates up and down.)

Now stretch the spring (increase the tension on the spring). What happens to the fundamental frequency?

You might also experiment with springs of different masses, e.g. a metal slinky and a lighter plastic slinky. How does mass affect the fundamental frequency if the springs are held at the same tension?