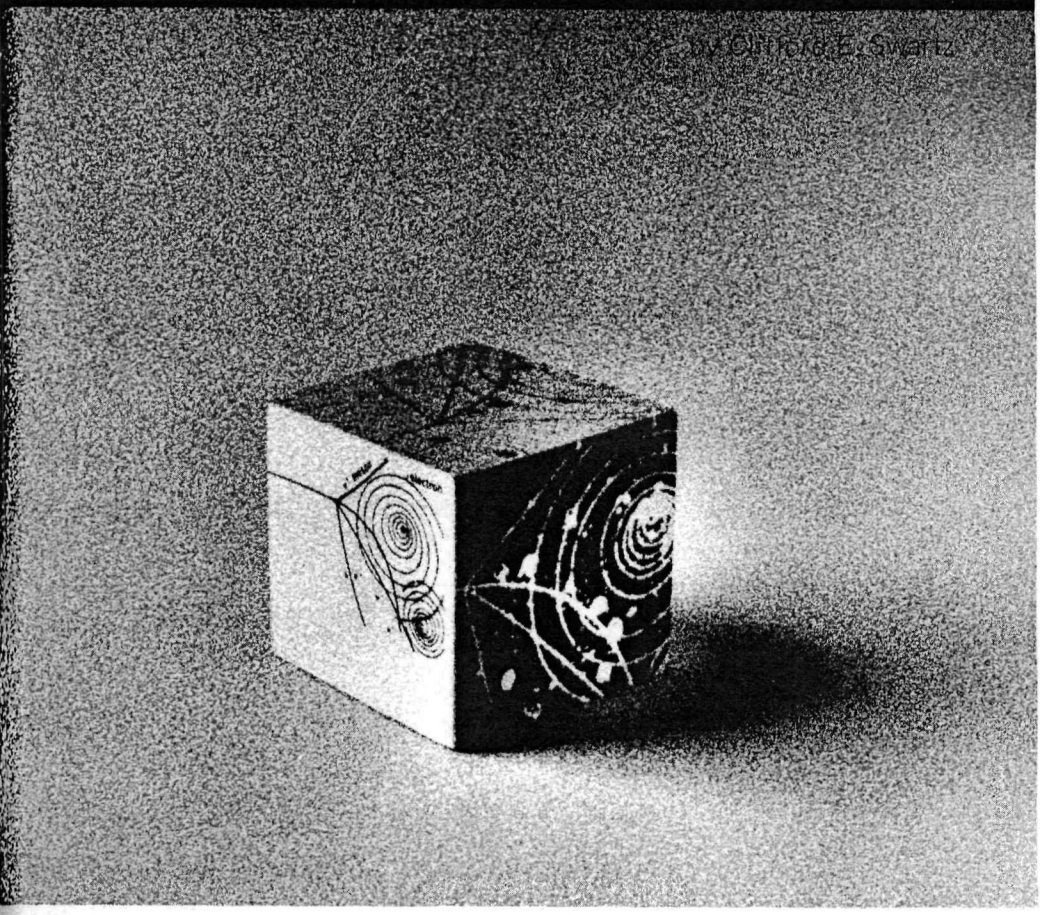
MICROSTRUCTURE OF MATTER

by Clifford E. Swartz



U.S. ATOMIC ENERGY COMMISSION
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Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

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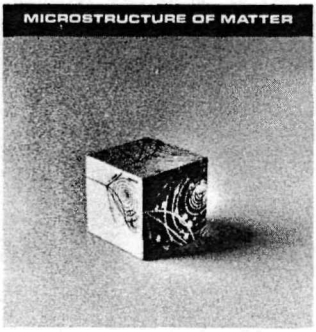

THE COVER

In this artist's conception, a cube, symbolic of the "building blocks" described in this booklet, carries on its surfaces photographs of bubble-chamber tracks made by some of the fundamental particles making up the Microstructure of Matter.

THE AUTHOR

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MICROSTRUCTURE OF MATTER

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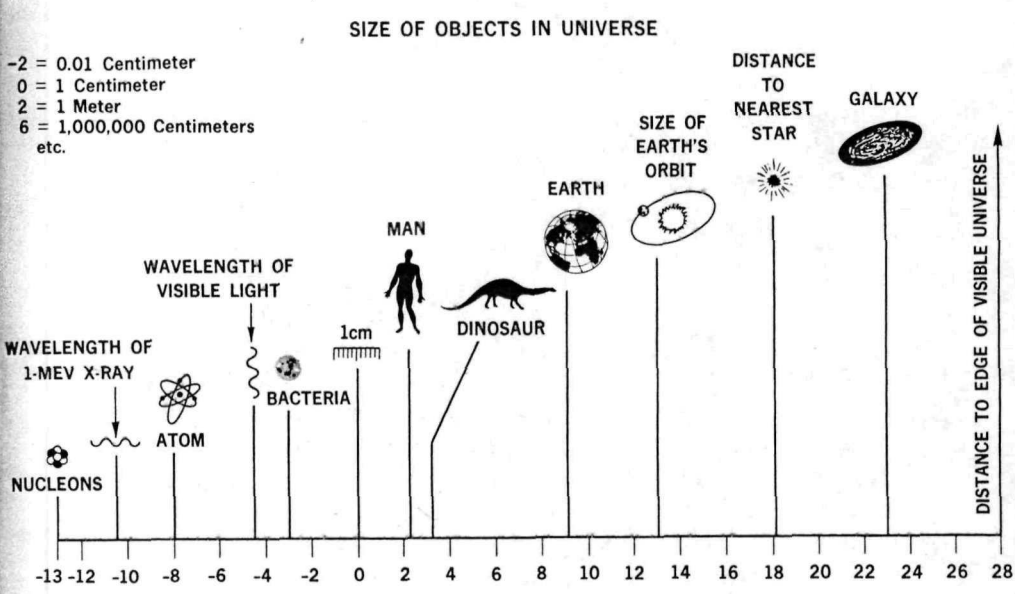
INTRODUCTION

Beyond our solar system and local galaxy of stars, ten billion other galactic systems swarm to the edges of the universe. Within each of our fingertips, each atom, a million times smaller than the width of a human hair, is, itself, ten thousand times as large as its central nucleus. This enormous range of sizes seems to defy unifying explanations (Figure 1).



Size is not the only obstacle to understanding the nature of matter. The material of the universe assumes a million different forms—gas, liquid, solid, animate, inanimate—thwarting any general classification.

Still, there has always been the feeling—or, at least, a wistful hope—that nature could be explained in terms of simple building blocks, which join together or break apart in simple ways. The Greeks thought that there might be basic atoms, out of which everything else could be formed. Empedocles, in 400 B.C., taught that everything was made from four elements and four essences. His geometric arrangement of these is shown in Figure 2. Ordinary substances were supposed to be composed of combinations of the pure elements linked by differing essences. Wood might appear to be made of earth, but if you added heat you could see that it also contained fire and air. The system was profound but useless; it was a mystic's scheme, leading only to alchemy and its vain efforts to turn lead into gold.

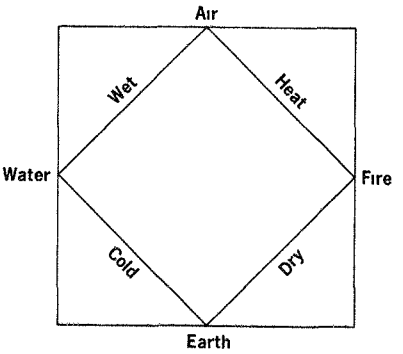


Figure 2 *The elements and essences of the Greek universe.*

Yet today we have arrived at a scheme of building blocks that superficially looks almost as sparse as that of the Greeks. In the last 40 years, we have torn apart the atoms that comprise the traditional 92 elements. We have learned to manipulate the cores of those atoms to realize, at last, the alchemists' dream of converting commonplace substances—not into gold, but into much more valuable radioactive materials. Since World War II, we have been busily tearing apart the protons and neutrons that make up the atomic nucleus. We find that there are several other particles besides protons, neutrons, and electrons, and it has become customary to refer to these as "elementary" or "fundamental" particles. Some of these other particles are listed in an introductory form in Figure 3. More detailed

PRELIMINARY CHART OF SOME OF THE PARTICLES

Family	Name	Symbol	Mass	Electric charge	Function and behavior
Proton-like particles	Omega	Ω	1.78 times proton	+ or −	Decays to lambda and K-meson.
	Xi	Ξ	1.40 times proton	+, −, 0	Decays to lambda and pi-meson.
	Sigma	Σ	1.27 times proton	+, −, 0	Decays to proton and pi-meson.
	Lambda	Λ	1.19 times proton	Zero	Decays to proton and pi-meson.
	Proton	p	1839 times electron	+ or −	Main constituents of atomic nuclei; in our world, protons are usually positive.
	Neutron	n	(1.7×10^{-24} gram)	Zero	
Nuclear-force agents	Eta-meson	η	1070 times electron	Zero	One of nuclear force agents when protons and neutrons are very close together.
	K-meson	K	970 times electron	+, −, 0	One of nuclear force agents when protons and neutrons are very close together.
	Pi-meson	π	270 times electron	+, −, 0	One of nuclear force agents. Exchange of mesons between protons and neutrons provides "nuclear glue".
Electron-like particles	Muon	μ	207 times electron	+ or −	Descendant of meson decays. Forms half of "cosmic rays" at sea level.
	Electron	e	$^1/_{1839}$ mass of proton	+ or −	Negative electrons in atom balance positive charge of nucleus.
	Neutrino	ν	Zero	Zero	Emitted in radioactive beta decay along with electron.
Massless bosons	Photon	γ	Zero	Zero	Agent of electromagnetic force (light, X rays, etc.).
	Graviton	-	Zero	Zero	Agent of gravitational force; not yet detected.

Only the proton, electron, neutrino, photon, and graviton are stable against radioactive decay A symbol with a superscript indicates a particle with a particular charge For example, π^0 (pi zero) is the zero-charge pi-meson

Figure 3

lists of particles and their properties are presented in Figure 21 on page 30 and in Figure 26 on page 43. If we count all these as particles, we have almost as many particles as there are elements. Surely they cannot all be "elementary" or "fundamental"! As we shall see, there are ways to classify them into a small number of basic types.

However they are organized, the particles make up the fine structure of matter with which this booklet deals. (This field of science is often referred to as particle physics or high-energy physics because of the fact that particle beams of extremely high energy are needed in most of its pertinent experiments.*)

*For background information on basic science relevant to this topic, see *Our Atomic World* and *Accelerators*, companion booklets in this series.

Before considering these classification schemes, we will examine, in the next section, the nature of particles and the properties by which we identify them. Most of what we know about them comes from the forces they exert on each other. These forces are presented in the second section, Interactions, or Forces. These interactions are subject to conservation laws, which are summarized in the third section. Finally, in the fourth section, new concepts are described in terms of which many particles may be thought of as different manifestations of a very few building blocks.

Although our main concern in this booklet is with the particles themselves and not with the machines with which they are created and observed, it is often necessary to know the nature of the instrument used in order to understand what is being observed. Appendix I gives a brief description of the tools of exploration in the microworld. Appendix II lists some of the particle groups and defines some of the language of the world of these particles. Appendix III tells how to interpret the particle-track pictures used in the booklet. You may wish to refer to these for information to help you understand what follows.

NATURE OF THE PARTICLES

Their Reality

Nearly everyone is familiar with the notion that all matter is made up of tiny atoms. As we think about ultimate tininess, we may be tempted to conclude that since atomic particles cannot be seen with ordinary light they must be merely theoretical notions rather than actual objects. But we can "see" atoms and even the particles inside them as definitely and as well as we can see a person on television. The process is no more complicated.

In a television studio, light is reflected from a man's face to the front screen of an electron tube. The light changes the electric charge on portions of the screen. A beam of electrons scans the screen and is reflected to an amplifier, which produces an image signal. Complicated electronic circuits turn the image signal into an electromagnetic wave signal. Miles away, your own TV set

receives the wave signal and transforms it into glowing regions on a phosphor screen. You "see" the man's face.

Now consider the operation of a bubble chamber that detects high-energy particles. The pressure in a container

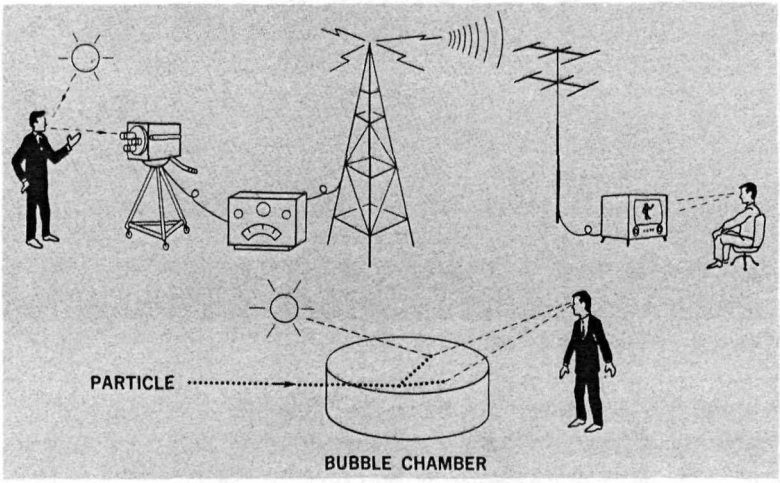


Figure 4 *The ease of seeing particles in a bubble chamber compared with that of seeing a man on television.*

of hot liquid is rapidly reduced so that the temperature of the liquid suddenly exceeds its boiling point. But, just before the liquid begins to boil and bubble, some nuclear particles from a high-energy "atom smasher" are sent through the container. They leave trails of damaged atoms that serve as "seeds" on which the first bubbles will form as the liquid begins to boil. A light is flashed, and our eyes, or a camera, can "see" the particles.

Actually we may see more of the particles in a bubble chamber than we can see of each other face-to-face. The particles apparently have only a few properties. All remain constant, and all can be measured. Compared to their reality, something as complex as a man is almost a theoretical notion.

Wave-Particle Duality

The familiar concept of the structure of an atom is shown in the model in Figure 5. Today mathematical models are regarded as more nearly correct since we know that an

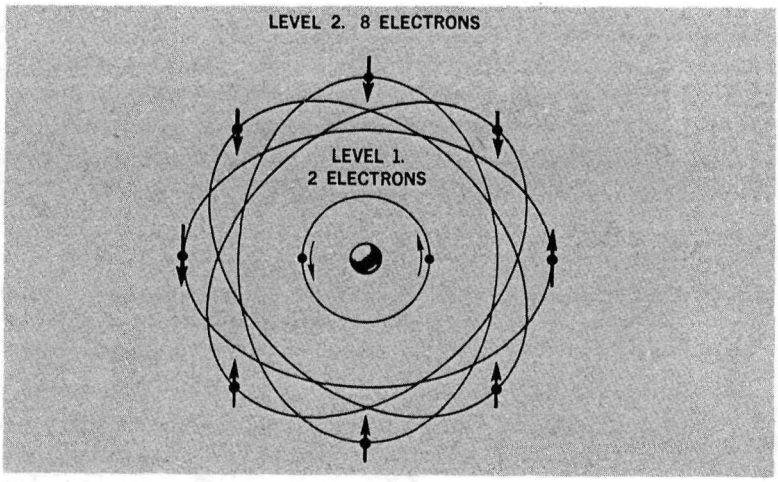


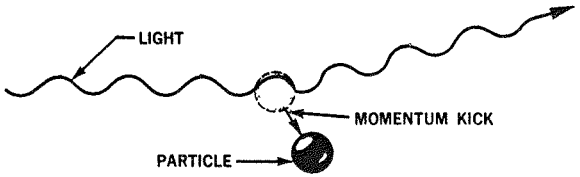
Figure 5 *The Bohr atom.*

electron's position, for example, cannot be measured accurately enough to justify picturing it in orbit around the nucleus. The mathematical description predicts the probability of finding the electron at different distances from the nucleus, and these predictions agree exactly with experiment. This vagueness with the electron orbits as pictured is typical of our difficulty in describing behavior of all the particles.

It is impossible to measure the *position* of a very small object without disturbing it with our measuring tool and thereby altering its velocity slightly. Similarly the *energy* of a moving system during a very short time interval is indefinite by an unknown amount. These tiny variations are insignificant in our everyday world, but on the atomic scale of time and distance they produce unexpected results. These relations between measurements of position and velocity, and between energy and time, are called "Heisenberg's Uncertainty Laws".* They are summarized in Figure 6.

The equations describing the motion of a particle tell us the *probability* that a particle will have certain values of position and velocity. Experimental findings confirm that there is a spread, or *probability distribution,* in the mea-

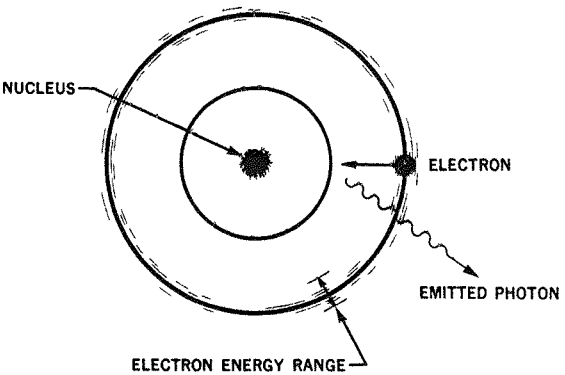
*First stated by Werner Heisenberg, German winner of the Nobel Prize for Physics in 1932.



Measurement of Position with Probe Disturbs Object

$$\Delta X \times \Delta p_x \geqq \hbar \approx 1 \times 10^{-34} \text{ joule-seconds}$$

This equation states that the uncertainty in the position times the uncertainty in the momentum must be greater than a very small constant (Planck's constant) Either can be measured with great precision but only at the expense of the precision in measurement of the other



Similarly a wave motion that has a beginning and an end cannot have a pure frequency, it must have overtones This corresponds to an uncertainty in the energy Stated as an equation, this is

$$\Delta E \times \Delta t \geqq \hbar \approx 1 \times 10^{-34} \text{ joule-seconds}$$

Figure 6 *Heisenberg's Uncertainty Relationships*

sured values. Particles with large momentum act very much like hard bullets, and so we expect the equations that describe their actions to be similar to those for bullets' actions. Their position at a given time should be quite definite. On the other hand, when low-momentum particles interact, their subsequent positions are more uncertain.

The mathematics describes this uncertainty in terms of probability. Solutions to the equations for low-momentum particles are very similar to the solutions of equations describing *wave motion.*

This does not mean that we must have two sets of equations or two different theories to describe the particles. Most equations describing physical events do not have complete, simple solutions. Instead, they are solved by making approximations.

For example, consider the equation describing a falling object:

$$F - KV^2 = MA$$

This tells us the force of gravity (F) minus the friction force of the air, which is proportional (K) to the square of the velocity (V) of the object, is equal to the mass (M) of the object times its acceleration (A). It is an approximation, however, to assume that the friction of air is proportional to the square of the velocity. The exact solution to the equation is complicated and requires the use of calculus. For two extreme cases, however, further approximations can be made so that solutions are simple. First, if the friction force is tiny because of streamlining of the falling object to produce a small value for K, we have the simple equation of free fall in a vacuum. Then the distance of fall is proportional to the square of the time of fall:

$$\Delta x = \tfrac{1}{2}\, at^2 \qquad \textit{Solution 1}$$

In the second case the friction may be very large. Parachutes fall with constant velocity, and marbles drop through molasses at a steady rate. In such events the solution to the equation is:

$$\Delta x = vt \qquad \textit{Solution 2}$$

This approximation changes the equation by making the friction force equal to the gravitational weight, and therefore the acceleration is zero.

No one imagines that we have produced a paradox because the same equation produces two different solutions; nor should we do so with equations describing actions of particles. Under certain experimental conditions the best approximation makes the equations similar to wave equations. In other experimental situations the proper approximation produces an equation similar to the kind describing the action of solid particles. We do not claim that the particle *is* a wave or *is* a hard particle; it merely behaves in this or that fashion under particular conditions. Nor should it be imagined that the particle moves with a wiggly, wavelike motion. It is the *probability function* which has a wave character, and this function can only predict the chances of finding particular values of position or velocity for a given particle at a particular time.

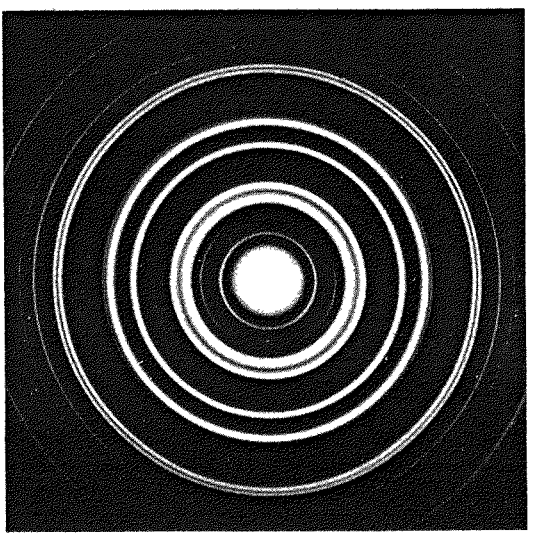


Figure 7 *Wave properties of particles.*
Courtesy Dr. Lester Germer

A demonstration of the wave properties of particles is shown in Figure 7. This interference pattern was produced by electrons shot through a thin foil. No electron, of course, really moved along a wavy path, but the wavelike *distribution* of electrons is described by mathematics of waves, and the alternate bright and dark lines in the photograph are similar to effects of interference phenomena in water waves or in light.

All of these remarks apply to the photon, the natural unit of electromagnetic radiation, as well as to the other particles. For long radio-wavelengths the best description of the photon is the wave model. For high-energy X rays the particle model is usually best. For visible light the wave model gives simple explanations of effects where the wavelength is about the same size as the object with which the light is interacting. For example, if light goes through a very small hole, it will spread out like a wave. On the other hand, if the object with which the light interacts is large compared with the wavelength, it is easier to describe the effect by making use of a particle model.

An example of the usefulness of both models can be seen in the shadow cast by parallel light rays (from a distant source) passing a knife edge. At first glance, the shadow is observed to have a very sharp boundary, as would be expected with streams of particles which either pass the knife edge or are blocked. Close examination of the shadow boundary, however, reveals that over very small distances the edge is indistinct and consists of close bands of light and shadow characteristic of wave action. There is no "duality" problem here, however. For some purposes light is best described by a particle model. Light is not a wave or a particle, however. Light is light.

Relativistic Effects

Another feature of particle behavior is that very often the particles are traveling almost as fast as the speed of light. As they approach this critical speed limit, relativistic effects (those explained by the Special Theory of Relativity) assume major importance. The most familiar of these effects is that energy and mass become interchangeable; that is,

$$E = mc^2$$

Particles with mass can be created out of surplus energy of other particles, and can decay back, losing their mass. An example of such creation is shown in Figure 8. Here a high-energy X ray, or gamma ray, turned all its energy into the mass and kinetic energy of two electrons, one

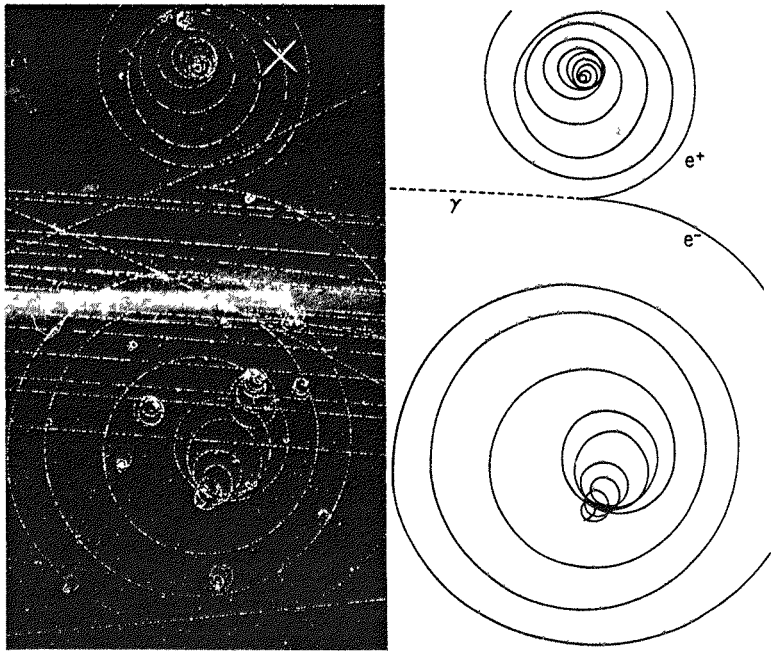


Figure 8 *Electron-pair creation.* Courtesy Brookhaven National Laboratory

positive and one negative. The inverse effect can be seen in Figure 9. An antiproton, which will be described later, collided with an ordinary proton. The mass of both was completely annihilated and turned into the mass and kinetic energy of new particles, mesons, which in turn decayed, yielding almost all their mass to the energy of yet lighter particles.

Another relativistic effect is change in the *duration of time* for objects traveling close to the speed of light. While you are reading this page, many particles called *muons* will go through your body. They are created near the top of the atmosphere by cosmic rays (protons) (Figure 10). When they are at rest, relative to us, they decay in a few millionths of a second. With that lifetime they should travel only a few hundred yards, even at the speed of light. The fact that many live to reach the earth shows that, at speeds close to the speed of light, time slows down for them.

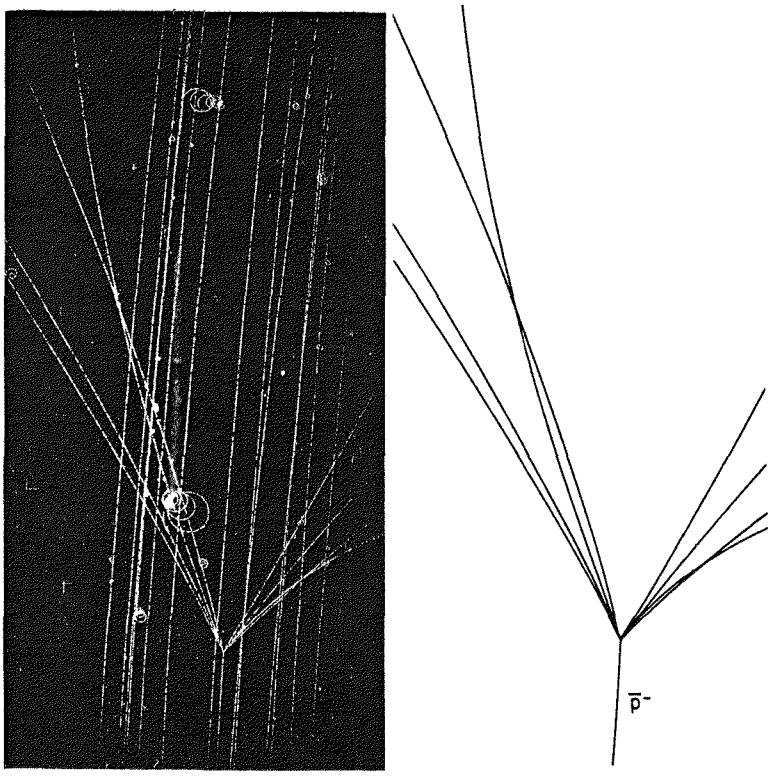


Figure 9 *Antiproton annihilation.* $\bar{p}^- + p^+ \rightarrow 4\pi^+ + 4\pi^- + x\pi^0$

Identification Properties

MASS-ENERGY We have said that there are only a few properties possessed by fundamental particles. Some of these are obvious enough. The particles have mass, although in a few cases the mass is zero—which is as reasonable a number as any other. The mass of particles is so small on the scale of pounds or grams that it is usually given in terms of the energy it would take to create the particle. Nature's unit of energy on the atomic scale is an amount about the size of the electron volt. This is the amount of energy needed to lift an electron (or any other particle with the electron's electrical charge) through a potential difference of 1 volt.

We call the electron volt nature's unit of energy because all chemical interactions on the molecular level involve

about 1 electron volt of energy. The photons of visible light, which can instigate such chemical changes, possess an energy of a couple of electron volts. Every time there is one molecular interaction in a flashlight battery, a single electron is lifted through a potential of $1\frac{1}{2}$ volts, using up $1\frac{1}{2}$ electron volts of chemical energy. On the human scale, this much energy is extremely small. It takes about 10^{19} such exchanges every second to power a flashlight bulb.

In the business of producing high-energy particles by accelerators, energies are usually expressed in millions of electron volts (Mev). For instance, a dentist's X-ray machine can accelerate electrons (to produce its X rays) to an energy of 0.1 Mev. The mass of an electron pair can be created with an expenditure of only 1.0 Mev.

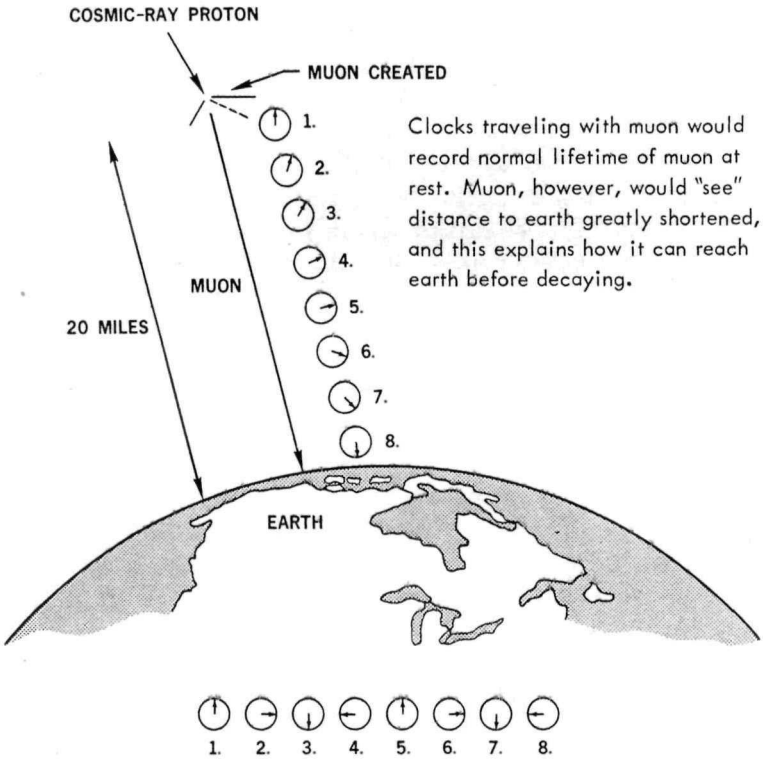


Figure 10

ELECTRIC CHARGE The particles can have an electric charge of +1, –1, or 0 times the basic unit of charge. At least one of the recently discovered short-lived resonance particles has a charge of +2.

SPIN Another property is angular momentum, or spin. Many particles behave as if they were spinning on a central axis, but only certain values of this spin appear. In terms of the basic unit of spin, most particles have 0 unit, ½ unit, or 1 unit. The difference between half-integral spin and integral spin (0, 1, 2, etc.) is profound. The half-integral spin particles, such as the electron, proton, and neutron, obey an exclusion "law" that "forbids" the existence of more than one of them in the same place. The integral spin particles, such as the photon and the meson, obey no such law.

Particle spin must produce observable effects, or the concept would be meaningless. We can best illustrate these effects in the case of the electron. If the electron is actually a spinning electric charge, it should also have the characteristics of a tiny magnet. In a magnetic field it should line itself up in the same direction as that of the field, much as a compass needle will point north–south in the earth's magnetic field. In a magnetic field that changes from strong to weak over a very small distance, a tiny magnet would move toward the region of stronger field.

In a famous experiment done in 1924, two German scientists, Otto Stern* and W. Gerlach, observed this movement of the electron magnets. The diagram in Figure 11 shows how the experiment was performed. If electrons had been shot through this nonuniform magnetic field, their sideways motion would have been much greater than any movement up or down because charged particles moving in a magnetic field are influenced by a force perpendicular to their direction of motion and perpendicular to the magnetic field. To avoid influence from this force, the experimenters shot neutral silver atoms through the system. It was conjectured that, because the atoms were neutral, they should

*Stern, who in his youth had been an associate of Einstein, was living in the United States when he received the Nobel Prize for Physics in 1943.

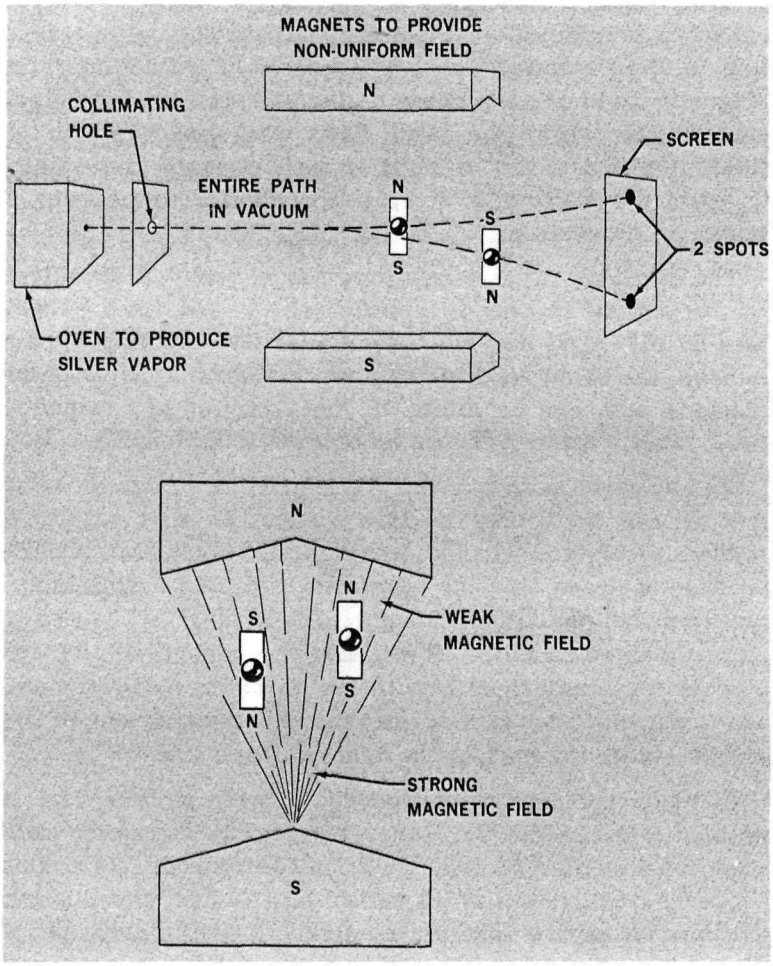


Figure 11 *Stern–Gerlach experiment that demonstrated quantized spin of electron.*

not be influenced by the magnetic field and thus should hit the screen along the center line. It turned out, however, that, although there is no magnetic effect associated with the complete atomic system, the outermost electron in a silver atom is free of the influence of the other electrons. For the purposes of this experiment, in other words, that electron is being carried along in a neutral system without any magnetic influence except that produced by its own spin.

If this spinning electron did act like a magnet, we would expect to find the silver atoms deposited all along a vertical line on the receiving plate. The amount of deflection in the magnetic field would depend on the orientation of the electron magnet within the atom. If it were lined up with the field, it would move down; if it were opposed to the field, it would move up; if it were perpendicular to the field, it would not move at all.

The startling result of the experiment was that the silver was deposited in only two positions—up and down. There was no silver in between. No matter how this experiment is done, the same result is always obtained. Apparently the electron spin can be either in the direction of a magnetic field or opposed to it, *but in no other orientation.*

We say that the spin of the electron is *quantized,* meaning that it can have only certain values. In this respect it resembles electric charge, which is also quantized. One is tempted to think that the electrons can really spin in any direction but that in the magnetic field they just happen to align themselves up or down. But the concept of electron spin is meaningless except in terms of its measurement, and when electron spin is measured it has only one of two values—with the measuring field or opposed to it.

Electron spin not only produces a magnetic effect but it is also responsible for other phenomena connected with *angular momentum,* which will be described later. One property of a system which cannot be changed, except from the outside, is its angular momentum. One application of this property to the electron concerns the beta decay of radioactive material. A decaying atom without any spin cannot shoot out an electron (a beta particle) which *is* spinning unless the atom recoils, spinning in the opposite sense. Experiments show, however, that during beta decay atoms change their spin by 1 unit or not at all, and never by $\frac{1}{2}$ unit, which would balance the electron spin. The explanation of the 1-unit atomic recoil, we now know, is that another particle, the neutrino—with spin of $\frac{1}{2}$ unit—is also emitted. There are many examples of electron interactions in which angular momentum due to electron spin must be taken into account.

In a magnetic field the possible orientation of a particle system depends on its total spin. The electron, with spin of $\frac{1}{2}$ unit, has only two possibilities. A system with spin 1 has three possible orientations—with the field, opposed to it, or perpendicular to it. The number of orientations is given by the formula:

$$\text{Possible orientations} = 2s + 1$$

where s is the spin. A picture model of these different possibilities is shown in Figure 12, and the spin of each particle is listed in Figure 21 on page 30.

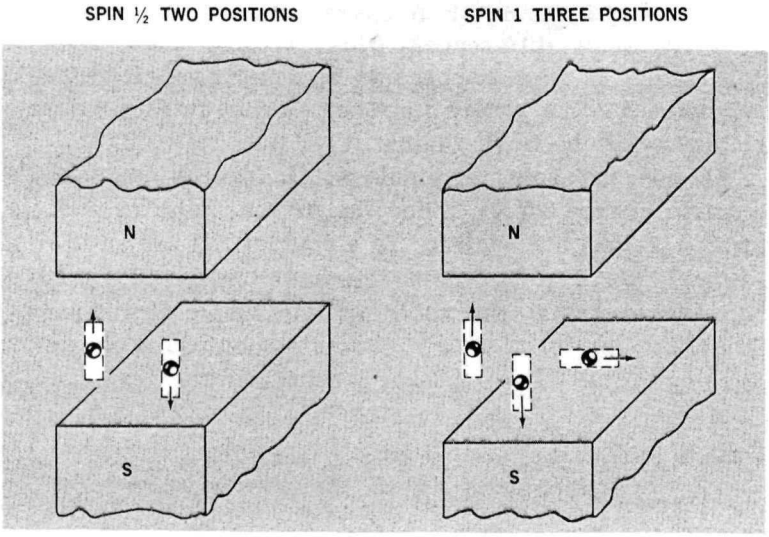


Figure 12 *Quantized orientations of spin in magnetic field.*

ISOTOPIC SPIN The properties of mass, electric charge, and rotational spin are familiar to us in everyday life. Some other properties of particles cannot be described in familiar terms. One of these has been given the name *isotopic spin* since its mathematics is much like that for rotational spin. However, no real spin is involved.

The chart of the particles in Figure 21 shows that most of the particles are members of groups arranged horizontally. Within each group the members have almost the same

mass. The pi-meson, for instance, is a triplet group containing π^+, π^-, and π^0. The proton and neutron are in many ways the same particle except for their electric charge effects. We consider them a doublet. The lambda zero, Λ^0, is a singlet. According to our present views, all members of multiplet groups have the same interaction with the Strong Nuclear Force (to be discussed later) but have different Electromagnetic Interactions, which are thought to be responsible for the slight mass differences among members of a multiplet.

One way of looking at this is to picture the members of a multiplet as being the same particle until the electromagnetic interaction is "turned on". Then the individual members assume different energy states, made apparent by their mass differences. This is very much like the description of what happens to spinning particles when a magnetic field is turned on. They assume different energy states—with the field, against it, or perpendicular to it.

We use the spin terminology, in fact, to describe the electric charge effect. Since the proton–neutron particle, usually called the nucleon, is a doublet, we assign to it an *isotopic spin,* $I = \frac{1}{2}$. When this isotopic spin is pointing "up", we say that the value of I in the up direction is I_3 (I-sub-three) $= +\frac{1}{2}$. This represents the proton. When I is pointing "down", $I_3 = -\frac{1}{2}$ and represents the neutron.

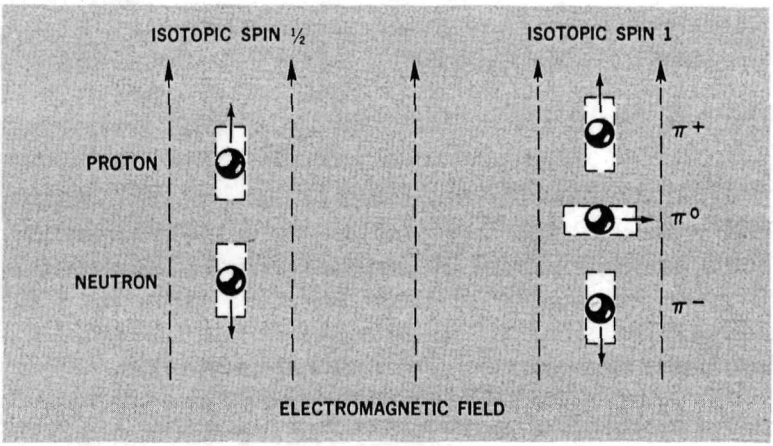


Figure 13 *Isotopic-spin multiplets.*

The pi-meson must have isotopic spin $I = 1$ so that it can assume three different orientations: $I_3 = +1$, $I_3 = 0$, $I_3 = -1$. The lambda zero, with only one possibility, must have isotopic spin of $I = 0$. These orientations of isotopic spin are illustrated in Figure 13. The numerical value of isotopic spin for each particle is given in Figure 21 on page 30.

STRANGENESS Another attribute that has no everyday counterpart is called *strangeness* It became necessary to assign *strangeness values* to some particles to account for a strange feature of their production and subsequent decay. These "strange" particles—the K-mesons, lambda zero, sigma, xi, and omega—are produced in high-energy collisions (in the billion-electron-volt range) but are remarkably stable; that is, they have relatively long lifetimes. There appears to be no reason why a lambda zero, for example, should not fall apart into a pi-meson and a proton in the same time in which it was made, the time it takes light to cross a proton diameter—about 10^{-23} second. Instead, it waits an eternity (on the nuclear time scale) and takes 10^{-10} second to decay. One way to explain this situation is to invent a special conservation law that describes what the particles do. (We will discuss other conservation laws in detail later.)

The conserved attribute is called *strangeness*, and we assign *strangeness values* to the particles in a way that will account for what we observe. For instance, the strange particles are always produced in pairs. A typical example of such associated production is shown in Figure 14. The lambda zero and the K zero are produced rapidly but decay slowly. We assign strangeness of $S = -1$ to the lambda and $S = +1$ to the K. During the production process, therefore, strangeness is conserved (-1 plus $+1$). Once the lambda and the K are separated from each other, they cannot decay without violating the strangeness conservation law because their decay products, protons and mesons, have strangeness numbers of zero. The strangeness conservation law is violated eventually by a decay that goes from $S = -1$ or $+1$ to $S = 0$, but it is a slow process. (The particular numbers of strangeness, S, shown in Figure 21 on page 30, were assigned to the particles that were known in 1957. With this scheme, predictions were then made that other

particles would be found and that certain reactions would occur and others would not. All these predictions have been fulfilled.)

HALF-LIFE Most of the particles are unstable and decay rapidly to other combinations. The chart of the particles (Figure 21) lists these decay times and decay routes, although these are not exactly basic properties of the particles. Rather, they are a description of the interactions and the various laws forbidding certain changes or conserving certain properties (mass–energy, electric charge, etc.). The particle decays follow the probability laws of radioactivity. That is, after the given half-life, half of the particles remain, and, after another such period, half of those remain. The times involved are extremely short on a human scale. A time of 10^{-10} second is one-tenth of a billionth of a second. Nevertheless, such times are measured fairly easily.

Notice the decays shown in the bubble chamber picture of Figures 14 and 15. Two neutral particles were formed, and they traveled for some distance (upward toward the top of the sketch), leaving no trails, until each decayed into two charged particles. The velocities of these neutral particles can be found by analyzing their decay tracks to find out their energies. They traveled several centimeters at a known constant speed, and therefore the time they traveled before the decay is:

$$t = \frac{\text{distance}}{\text{velocity}}$$

There may be complications in the computation because of the relativistic slowing of time if the particles were traveling close to the speed of light, but this factor can be taken into account. If many such measurements are made, the half-lives of the particles can be calculated with great precision. Even shorter times—as small as 10^{-22} second—can be measured with considerable certainty by indirect methods. That brief interval is about ten times as long as it takes light to cross the diameter of a single nuclear particle.

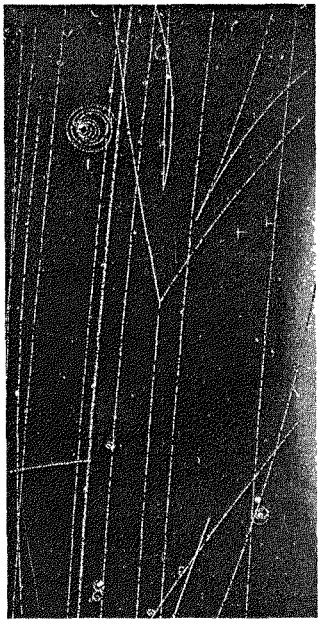


Figure 14 *Photograph of the pair production of strange particles.*

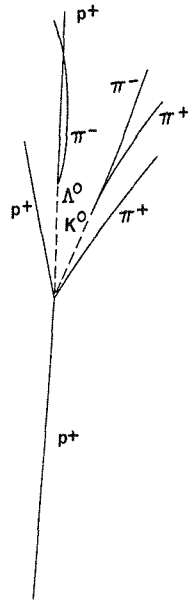


Figure 15 *Sketch of the photograph in Figure 14 with the particles labeled.*

PARTICLE-ANTIPARTICLE One other aspect of the particle chart requires explanation. All particles have antiparticles. These have all been produced and are as real as the particles themselves. The track left by the antielectron—the positron—is shown in Figure 8, and most of the tracks in Figure 9 were made by antiprotons. The antiparticles are as stable, or as unstable, as their counterparts, but in our section of the universe they are in the minority. Whenever an antiparticle meets its corresponding particle, the two annihilate each other, their mass turning into other forms of energy.

A universe consisting of atoms with antiprotons and antineutrons in their nuclei and with positrons in their outer shells would be perfectly stable. Why our "local" situation exists is not known. Perhaps some of the distant galaxies are composed of antimatter.

The electric charge and strangeness number of an antiparticle are opposite to those of its particle. Thus the

antiproton is negative, and the positron (antielectron) is positive. The antineutrons are necessarily neutral, but when produced by the high-energy accelerators they meet and annihilate ordinary neutrons just as expected. A few of the particles—η^0, π^0, γ—serve as their own antiparticles.

INTERACTIONS, OR FORCES

We know about any object in this world only because of its interactions with other objects. It might seem, in fact, that the world is as complicated as it is because there are so many different expressions of forces, or interactions. There are forces exerted by springs, muscles, wind, expanding gas, gravity, physical contact, magnetism, electricity, and on and on. But in truth we know of only four *types* of force in all the universe. All others are merely manifestations of the four basic kinds.

Gravity

Gravity is the first force we experience. When we are still infants, we begin to cry if our support gives way and Gravity pulls us down. The great English scientist Isaac Newton gave a successful description of Gravity over 300 years ago. Although the interpretation of this force on a cosmological scale was altered by Albert Einstein's General Theory of Relativity, Newton's original formula is still satisfactory for most purposes. Even at galactic distances the corrections required by General Relativity are small.

Gravity is a simple type of force compared with the other three. Let us examine its features. The basic formula is so familiar that it is easy to forget how remarkable it is.

$$F = G\frac{mM}{r^2}$$

This equation says that the force (F) between two objects is proportional to the product of their masses (m and M) and is inversely proportional to the square of the distance (r) between them. The constant (G) is necessary to make

the units appropriate. Its value depends on whether the mass is measured in pounds or grams or English stone weights and whether length is measured in meters or furlongs.

Note first of all that the force is always attractive. So far as we know, there is no way to produce gravitational repulsion. Second, the force between the objects is directed along the straight line between them. This seems like a straightforward way to have a force act between objects, but it is not the only way; the Electromagnetic Force (to be discussed next) can be directed at right angles to the line between interacting objects. Furthermore, the gravitational force does not depend on the velocity or the orientation of the objects as some other forces do.

The dependence of the force on the inverse square of the separation distance has more to do with the nature of space than with Gravity. The formula applies only to spherical objects or to objects that are far apart compared with their own size. Any influence spreading out from a small region without being absorbed decreases with an inverse-square dependence on distance. The reason can be seen in Figure 16.

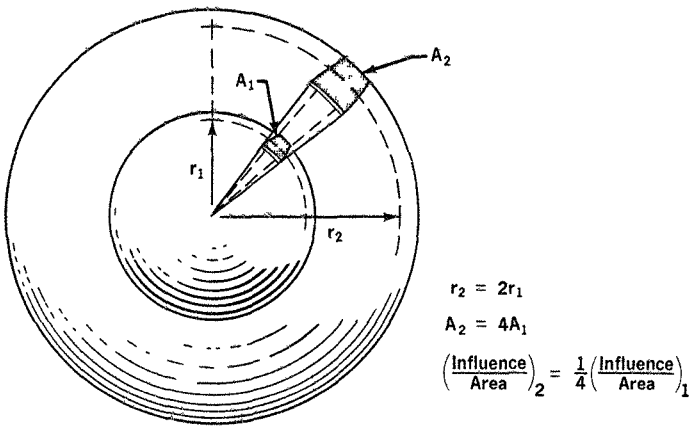


Figure 16 *Influence per square centimeter decreases as the square of the distance from the source. The reason for this is that the influence must cover all the area of a spherical shell at a particular distance and the area of a sphere is $4\pi r^2$.*

The most startling characteristic of Newton's law is that the "charge", or source of the gravitational influence, is *mass*. We use the word "mass" to describe a property that shows up in two completely different kinds of experiments. First of all, it is the source of the gravitational pull and thus determines the weight of an object. In the gravitation formula, for instance, m might be the mass of an object, M the mass of the earth, and r the radius of the earth. Then F is the weight of the object when it is on the surface of the earth. But m also is the proportionality constant in Newton's other famous law relating the acceleration of an object to the applied force:

$$F = ma$$

In this case m is a measure of inertia, the reluctance of an object to having its velocity changed. Why should this *inertial mass* also be the source of an attractive force between two objects? The situation, indeed, is that gravitational mass is identical with inertial mass. It took an Einstein to build the consequences of this identity into the General Theory of Relativity.

Electromagnetism

We link electricity and magnetism together because they are both part of the same phenomenon. The force between two electric charges depends, among other things, on their relative velocity. If they are at rest with respect to each other, they experience only an electrostatic force. If they are moving, they also exert magnetic forces on each other.

When the charges are at rest, the force can be described with Coulomb's* law:

$$F = K \frac{q_1 q_2}{r^2}$$

At first glance, this formula looks much like Newton's law of gravitation. The dependence on the inverse square of the

*Named for Charles A. Coulomb, French physicist who first stated this law.

separation of the charges (q_1 and q_2) is again due to the nature of space and the fact that the formula applies only to charged objects much smaller than the separation distance. The constant K regulates the units properly. In this case, however, the charges can be plus or minus, and the force can thus be attractive or repulsive.

If one electric charge is moving past another, the magnetic force produced is proportional to the velocity of the movement and acts in a direction perpendicular to the velocity and to the line separating the two charges. Furthermore, if an electric charge accelerates, an entirely different phenomenon appears. Radiant energy is emitted which goes off with the speed of light. This is an important source of electromagnetic radiation—light, radio, infrared, and X rays (Figure 17).

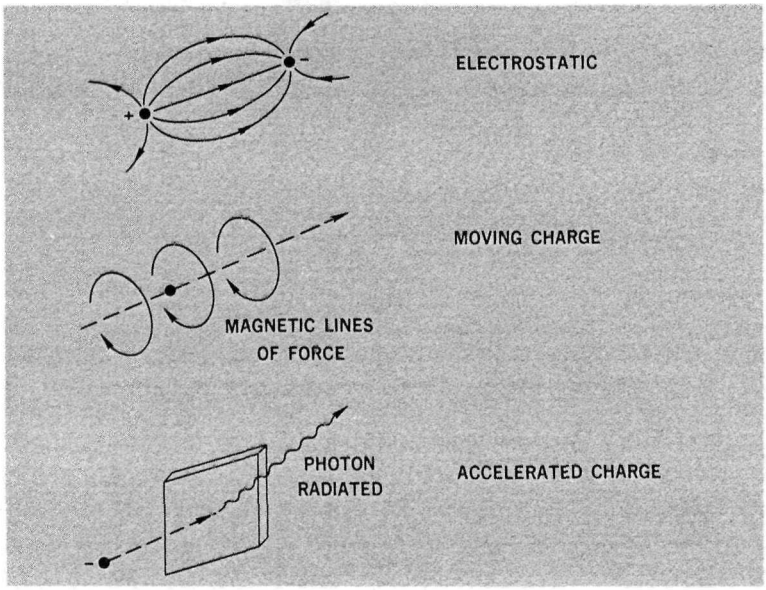


Figure 17 *Electromagnetic phenomena are velocity dependent.*

The Electromagnetic Force is responsible for most of the force we experience in everyday life. It holds the electrons to the atoms and the atoms to each other and therefore is the source of all chemical binding. The force exerted by a spring can be traced directly to the electromagnetic attractions between displaced atoms in the crystal

structure of the metal. The energy for an explosion of dynamite comes from the release of chemical energy, which is electromagnetic. When expanding gases impinge on the walls of a container, the repulsive force exerted on the bombarding molecules is also electromagnetic since they are repelled by the distortions of their electron configurations. All biological processes can be described (when they are known) by molecular transformations, which are controlled by Electromagnetic Forces.

Strong Nuclear Force

Both Gravity and Electromagnetism have been known for some time, but it was not apparent until this century was well along that there was a third type of force—in the nuclei of atoms. In 1933, when the neutron was discovered,

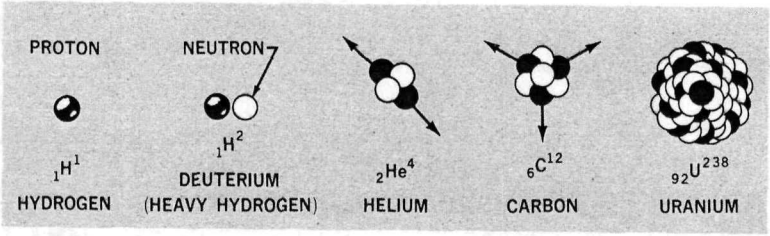


Figure 18 *Nuclei are composed of protons and neutrons held tightly together in spite of the electrostatic repulsion of the protons.*

the picture of the atomic nucleus was outlined essentially as we know it today. As illustrated in Figure 18, the nucleus contains both protons and neutrons. All their characteristics are listed in Figure 21, but for now the important point is that the protons have positive electric charge and the neutrons have no charge. Nevertheless, they stick very tightly, as if they were so many marbles glued together. The problem is: Since like charges repel, why doesn't the electrostatic repulsion of the protons make the whole assembly explode? The gravitational attraction, as we shall see shortly, is far too weak to bind the nucleus together. There must be another force acting between the nuclear particles which is stronger than the repulsive force of Electromagnetism.

Thirty years of research have led to a good qualitative description of this Strong Nuclear Force, but not to a complete quantitative theory. We cannot write a formula as was done for Gravity and Electromagnetism. The most important property of the force is that it is short-range. If the nuclear particles are touching each other—within 10^{-12} centimeter—the force is very strong. Outside this range the force falls rapidly to zero. In this respect it acts something like Scotch tape in holding the nucleus together, but for quite different reasons. The strength of this nuclear force depends on the orientation of the protons and neutrons. They act as if they were spinning, and it makes a difference whether they are spinning in the same direction or in opposite directions.

Weak Interaction

Although the great physicist Enrico Fermi* worked out some of the rules for the fourth type of force, the Weak Interaction, in 1933, its significance was not well understood until the past decade. Even today we know very little about the Weak Interaction, and some of the most exciting work now being done with the large particle accelerators is concerned with its effects. The Weak Interaction is responsible for and helps explain the natural radioactive decay of nuclei that emit beta rays (electrons). Many of the new particles that have been discovered in the last 15 years also decay because of the Weak Interaction. So little is known about it that no range of influence can be given, and, of course, no formula can be written to describe its influence (Figure 19).

BETA DECAY $Co^{60} \rightarrow Ni^{60} + e^- + \bar{\nu}$ DECAY OF MUON

Figure 19 *Decays allowed by weak interaction.*

*Winner of the Nobel Prize for Physics in 1938. An Italian, Fermi lived in the United States after receiving this award.

Comparison of the Interactions

These four—Gravity, Electromagnetism, the Strong Nuclear Force, and the Weak Interaction—are all the forces that exist. So far as we know, there are no other ways in which the basic building blocks of matter can interact with one another. We now know how to calculate, at least in principle, the results of any experiment we know how to do involving Electromagnetism or Gravity. Even with the qualification this is a bold claim. Still, the forces involved are known. There remains the possibility that Gravity and Electromagnetism are linked in some way which we do not now understand, although we do not know that there is such a link and there is no situation involving the two forces which cannot be explained with our present theories.

In contrast, there is no general theory describing the Strong Nuclear Force, although we know enough about it to transmute elements and derive power from the fission of heavy nuclei. Part of the trouble is that, since many particles have large effects on each other while they are bound in a nucleus, calculations of the total effect are extremely difficult. This is not the case with the Weak Interaction. Too little is known about its nature to form even a qualitative picture.

We have called the nuclear binding force "strong" and the decay force "weak". Let us indicate the reason for these designations by comparing the strengths of the four interactions. If two protons are touching each other, the Strong Nuclear Force can be 100 times greater than the electromagnetic repulsion. The Weak Interaction is smaller than the Strong Nuclear Force by a factor of 10 million million (10^{13}). And the gravitational attraction, the weakest of all, is smaller than the Strong Nuclear Force by a factor of 10^{39}! (The reason Gravity seems so important to us is that it is a relatively long-range force. Our weight, for example, represents the attraction of 10^{51} nuclear particles in the earth to 10^{29} within our own body.) The effects of Gravity are completely negligible in individual nuclear or atomic reactions. At the other end of the scale, Gravity dominates the interactions of stars and galaxies.

Model of the Way Particles Interact

How do these building blocks of matter (particles) interact through these forces? We can answer this with great success mathematically. Gravitational and electromagnetic effects are thought to be achieved by a sort of warping of space—that is, by establishment of gravitational or electromagnetic fields. This concept is very satisfactory for many purposes; and it is not at all at odds with another model, which pictures the sources, or "charges", of each of the forces as emitting some sort of "agents", which impinge upon other, similar sources.

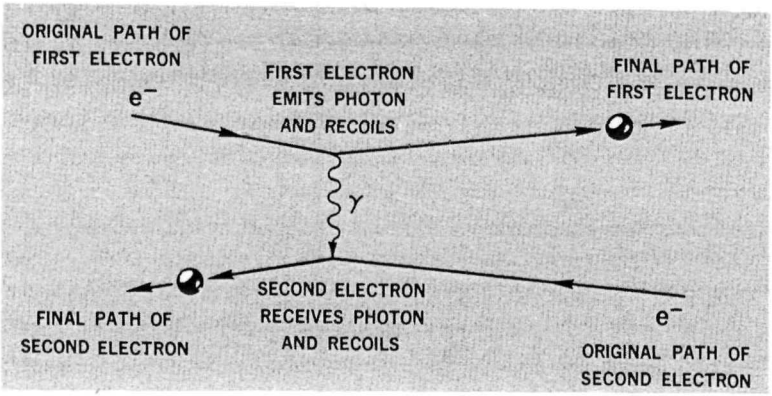


Figure 20 *Interaction of two electrically charged particles by way of a photon agent.*

Instead of viewing the influence of one "charge" on another as a continuous process due to their interaction with each other's fields, we picture a whole series of individual collisions taking place between the charges and their agents. The interchange of these messengers produces the binding force (or, in some cases, the repulsion). This description has been highly successful in explaining the Electromagnetic Force. In this case the propagating agents are photons, which are electromagnetic radiation. Figure 20 illustrates how electric charges interact by collisions with photons.

The same type of theory has been worked out for Gravity, and the supposed agents have been named *gravitons*. Because this interaction is so extremely weak, we have not

PARTICLES STABLE AGAINST STRONG NUCLEAR DECAY

CLASS	NAME	PARTICLES	ANTIPARTICLES	REST MASS IN Mev	HALF-LIFE IN SECONDS	DECAY SCHEMES
BARYONS STRONGLY INTERACTING FERMIONS (SPIN IS HALF INTEGRAL $\hbar$)	OMEGA HYPERON ISOTOPIC SPIN I = 0 SPIN = $3/2\,\hbar$	$S=-3$: Ω^-	$S=+3$: $\bar{\Omega}^+$	1676	$\sim 10^{-10}$	$\Omega^- \rightarrow \Lambda^0 + K^-$
	CASCADE HYPERON $I = 1/2\,\hbar$ SPIN = $1/2\,\hbar$	$S=-2$: Ξ^0 Ξ^-	$S=+2$: $\bar{\Xi}^+$ $\bar{\Xi}^0$	$\Xi^\pm \approx 1320$	0.9×10^{-10}	$\Xi^- \rightarrow \Lambda^0 + \pi^-$
				$\Xi^0 \approx 1310$	1.0×10^{-10}	$\Xi^0 \rightarrow \Lambda^0 + \pi^0$
	SIGMA HYPERON $I = 1$ SPIN = $1/2\,\hbar$	$S=-1$: Σ^+ ($I_3 = 1$) Σ^0 ($I_3 = 0$) Σ^- ($I_3 = -1$)	$S=+1$: $\bar{\Sigma}^+$ ($I_3 = +1$) $\bar{\Sigma}^0$ ($I_3 = 0$) $\bar{\Sigma}^-$ ($I_3 = -1$)	≈ 1190	0.6×10^{-10}	$\Sigma^+ \rightarrow p^+ + \pi^0$ (50%) $\Sigma^+ \rightarrow n^0 + \pi^+$ (50%)
					$< 10^{-12}$	$\Sigma^0 \rightarrow \Lambda^0 + \gamma$
					1.2×10^{-10}	$\Sigma^- \rightarrow n^0 + \pi^-$
	LAMBDA HYPERON $I = 0$ SPIN = $1/2\,\hbar$	$S=-1$: Λ^0	$S=+1$: $\bar{\Lambda}^0$	1115	1.7×10^{-10}	$\Lambda^0 \rightarrow p^+ + \pi^-$ (67%) $\Lambda^0 \rightarrow n^0 + \pi^0$ (33%)
	NUCLEON (PROTON-NEUTRON) $I = 1/2$ SPIN = $1/2\,\hbar$	BARYON CHARGE CENTER: p^+ ($I_3 = +1/2$) n^0 ($I_3 = -1/2$)	ANTIBARYON CHARGE CENTER: $\bar{n}^0$ ($I_3 = +1/2$) $\bar{p}^-$ ($I_3 = -1/2$)	939.5	0.7×10^3	$n^0 \rightarrow p^+ + e^- + \bar{\nu}$
				938.2	STABLE	
MESONS STRONGLY INTERACTING BOSONS (SPIN = 0)	η-MESON $I = 0$	HEAVY MESON CHARGE CENTER: η^0		548	$< 10^{-16}$	$\eta^0 \rightarrow \pi^+ + \pi^- + \pi^0$
	K-MESON $I = 1/2$	$S=+1$: K^+ ($I_3 = +1/2$) K^0 ($I_3 = -1/2$) $S=-1$: $\bar{K}^0$ ($I_3 = +1/2$) $\bar{K}^-$ ($I_3 = -1/2$)		$(\bar{K}^- = K^+)$ 494	0.8×10^{-8}	$K^+ \rightarrow \pi^0 + e^+ + \nu$ (5%) $K^+ \rightarrow \pi^0 + \mu^+ + \nu$ (5%) $K^+ \rightarrow \mu^+ + \nu$ (64%) $K^+ \rightarrow \pi^+ + \pi^0$ (19%) $K^+ \rightarrow 2\pi^+ + \pi^-$ (6%) $K^+ \rightarrow \pi^+ + 2\pi^0$ (2%)
				$K^0 \rightarrow K_1^0$, $\bar{K}^0 \rightarrow K_2^0$: 498	0.7×10^{-10}	$K_1^0 \rightarrow \pi^+ + \pi^-$ (≈ 34%) $K_1^0 \rightarrow 2\pi^0$ (≈ 16%)
					4×10^{-8}	$K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$, $K_2^0 \rightarrow 3\pi^0$ (7%) $K_2^0 \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}$ (19%) $K_2^0 \rightarrow \pi^\pm + e^\mp + \nu$ (24%)
	PI-MESON $I = 1$	$S=+1$: π^+ ($I_3 = +1$) π^0 ($I_3 = 0$) π^- ($I_3 = -1$)		π^- 140	1.8×10^{-8}	$\pi^- \rightarrow \mu^- + \bar{\nu}$
				π^0 135	0.7×10^{-16}	$\pi^0 \rightarrow \gamma + \gamma$ ($\pi^0 \rightarrow \gamma + e^+ + e^-$ 1%)
				π^+ 140	1.8×10^{-8}	$\pi^- \rightarrow \mu^+ + \nu$ ($\pi^+ \rightarrow e^+ + \nu$ 0.01%)
LEPTONS WEAKLY INTERACTING FERMIONS (SPIN = $1/2\,\hbar$)	MUON	μ^-	μ^+	105.7	1.5×10^{-6}	$\mu^- \rightarrow e^- + \nu + \bar{\nu}$
	ELECTRON	e^-	e^+ (POSITRON)	0.51	STABLE	
	NEUTRINO-MUON	ν_μ	$\bar{\nu}_\mu$	0	The neutrinos associated with $\mu^\pm$ are different from those with $e^\pm$	
	NEUTRINO-ELECTRON	ν_e	$\bar{\nu}_e$	0		
MASSLESS BOSONS (SPIN = $1\,\hbar$)	PHOTON	γ		0	STABLE	
MASSLESS BOSONS (SPIN = $2\,\hbar$)	GRAVITON ?			0	STABLE	NOT DETECTED

Figure 21

been able to detect gravitons with our present instruments, although experimental attempts are being made to find them. Consequently the theory has not been very fruitful.

The same model was used by the Japanese physicist Hideki Yukawa* in 1935 to explain the Strong Nuclear Force. Because of the strength and the short-range nature of this force, the agent that makes it effective must have mass (the photon has none). This agent of the nuclear force is the *meson,* which is described later. Qualitatively, interchange of mesons could provide the nuclear binding force; but it turns out that there are several mesons, and there is much that we do not know about them yet.

Attempts to find an appropriate agent of the Weak Interaction are being made at two great research centers, the Atomic Energy Commission's Brookhaven National Laboratory on Long Island, New York, and the cooperative European laboratory, CERN, at Geneva, Switzerland.

CONSERVATION LAWS

A productive way to learn how things change is to discover in what ways they remain constant. Even simple events—such as the collision of two balls—are difficult to describe in terms of the forces acting at each instant. If, however, we do not attempt to explain in detail what happens during the collision but look only at the final results, we can make some very general statements. Certain properties of the event always remain constant.

Mass-Energy

Almost everyone is familiar with some of the conservation laws.† Many grade school children know that energy is conserved before they know what energy is. Lest familiarity breed indifference, let us emphasize a few points about energy conservation.

In the first place, when we say that a property is conserved, we are talking about what happens in a particular, limited system which we can isolate either physically or in

*Winner of the Nobel Prize for Physics in 1949.

†These laws state, in general terms, that matter, energy, momentum, etc., can be neither created nor destroyed.

imagination. The total energy of two colliding balls is not conserved if one of them is fastened to a spring; in that case we have to consider the energy system that includes the spring.

Second, we now realize that mass and energy are interchangeable in a way not too different from the interchangeability of kinetic and potential energy. Therefore we say that the *total* mass–energy of an isolated system is conserved.

Finally, we should recognize that although the conservation laws yield very profound insights into the regularities of nature, to some extent they are man-made. As an example, if we use up kinetic energy in rubbing two sticks together, we may feel that the energy is not conserved since the sticks acquire no new energy. But the sticks become hot, and so we say that the kinetic energy has turned into heat energy. In some school experiments an attempt is made to *prove* the conservation of energy by measuring the temperature rise in the sticks and showing that the heat energy in calories is equal to the kinetic energy producing it.

The logic of this situation is really quite different. The heat energy is indeed equal to the kinetic energy because it was *defined* to be equal in order to satisfy the conservation law. In fact, that is the way all relationships of energy exchange were worked out. Do not think that it is just a matter of definition, however. The remarkable conservation laws consistently work in an enormous number of applications.

The conservation laws apply also to the microworld of particles, although this had to be demonstrated at every step toward our present understanding. In the late 1920s physicists determined that the energy detected in beta decay of naturally radioactive atoms was much less than the total change of energy in the decaying nuclei. To explain this in terms of the energy conservation law, as well as to account for other features of the process, Wolfgang Pauli* proposed in 1933 that a lightweight, uncharged particle must be emitted during beta decay with the electron. This particle,

*Austrian physicist who won the Nobel Prize for Physics in 1945.

called the neutrino, was not actually detected until 1956, when Frederick Reines and Clyde L. Cowan, American physicists, discovered it at the AEC's Savannah River Plant in South Carolina after conducting a preliminary experiment near one of the giant nuclear reactors at the AEC's Hanford Plant in the state of Washington. Meanwhile, however, very few physicists had doubted that the neutrino existed.

Momentum

The total momentum of a system is conserved also. At low velocities, momentum is the product of mass and velocity. At velocities close to the speed of light, the mass of an object is greater than it is when at rest. So the momentum of a particle can get larger and larger in spite of the fact that its velocity approaches a speed limit. For particles at relativistic speeds, momentum is a more fundamental quantity and is more easily measured than either mass or velocity separately. (See Figure 22.)

Angular (Rotational) Momentum

Angular momentum is an extremely important property of elementary particle systems. On a human scale it is related to the product of ordinary momentum and the length of the radius arm pointing from the moving object to a point around which it is rotating or about which it might rotate. Angular momentum is a vector with a definite direction, and both this direction and the magnitude remain constant in an isolated system. Because of this we can balance bicycles while they are moving but not while they are standing still. Because angular momentum is con-

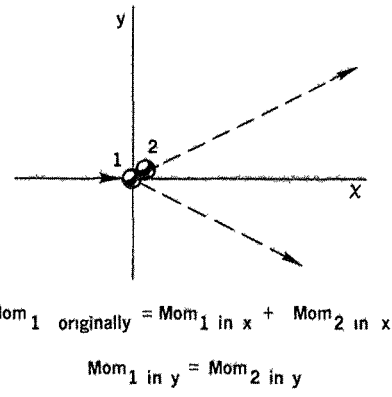


Figure 22 *Conservation of momentum in particle collision.*

served, a figure skater can twirl faster and faster on one toe. She starts her spin with arms outstretched so that the mass-times-velocity-times-radius-arm is large. When she draws her arms in close to her body, the radius arm becomes small and the velocity must increase to compensate since the total product must remain the same. As we have already seen, many of the particles have intrinsic angular momentum, which we call spin, as well as angular momentum due to their motion around each other.

Electric Charge

Electric charge is conserved if a positive particle and a negative one collide; they neutralize each other, but a positive particle can never break down into a neutral particle alone. If particles are created or annihilated, there must be an equal number of positive and negative particles affected. An example of electron production from a neutral gamma ray is shown in Figure 8. Note that both positive and negative electrons are produced.

Leptons and Baryons

There appear to be two conservation laws associated with two families of particles. Figure 21 groups together electrons, muons, and neutrinos into a class of light particles called *leptons*. The nucleons and heavier particles are called *baryons*. The total number of leptons in the universe remains constant and the total number of baryons remains constant. To be sure, antiprotons and antielectrons can be produced, but only if ordinary baryons or leptons are also produced in the same process. When the positron—the antielectron—is annihilated, it takes with it an electron.

Strangeness and Isotopic Spin

The conservation laws listed so far apply to all types of interactions. There are, however, some conservation laws that do not hold for one or more of the four types of forces. For instance, the total strangeness value of a particle system remains constant when the Strong Nuclear and the Electromagnetic Interactions are in control; but the Weak

Interaction can, after a delay, violate the law. The total isotopic spin cannot change in Strong Nuclear Interaction, but it can in both Electromagnetic and Weak Interactions.

Parity

One other limited conservation law must be mentioned because until a few years ago no one thought that it was limited. In the mathematical description of particles and their interactions, it is possible to describe particles so that, if all the coordinates (x, y, and z) are reversed and made negative, the resulting description will either be identical to or have exactly the negative value of the previous description. This mathematical property is called *parity*, and it is either even or odd, depending on whether the resulting description remains positive or turns negative. (For example, the sine function of an angle has odd parity; the cosine function has even parity.)

It was believed until recently that there was an absolute conservation law of parity. If the description of a system had even parity before an interaction, it must have even parity after. The implication of this for the physical world was that any process could work just as well in a "mirror world" as in a real world. Of course, we have our local human peculiarities of driving on the right side of the road and having our clock hands turn clockwise; but it was thought that all particle processes were completely independent of our definitions of right–left or clockwise–counterclockwise and that nature had no preference.

In 1958 T. D. Lee and C. N. Yang* pointed out that, although nature did not favor clockwise over counterclockwise in the everyday world controlled by the Strong Nuclear and Electromagnetic Forces, no such evidence existed for the world of the Weak Interaction. Their suggestion was immediately tested with beta decay, which takes place through the Weak Interaction, and with some of the new strange particles. True to expectations, the electrons of beta decay come out preferably in one direction. The decay of strange particles is such that one of the decay products

*American physicists who shared the Nobel Prize for Physics in 1957.

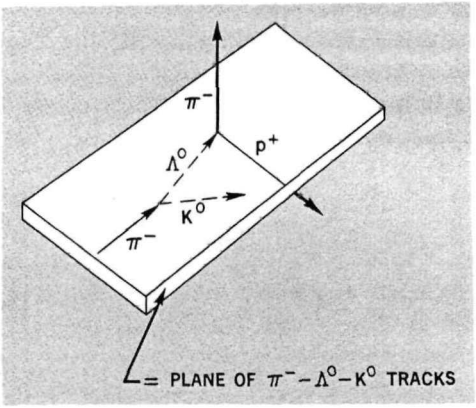


Figure 23 *Violation of parity in Weak Interaction decay of Λ^0. The π^- heads preferably in one direction out of the production plane, thus defining "up".*

usually comes out on only one particular side of the plane defined by the particle motions (Figure 23). In the Weak Interactions, then, parity is *not* conserved, and nature *does* distinguish between right and left, up and down, and clockwise and counterclockwise.

There is a catch to this distinction, however. For antiparticles the natural preferences are just reversed. Anticobalt emitting antielectrons would shoot them preferentially in the opposite direction to that preferred by cobalt. For some reason the direction sense of space seems to be tied up with particle–antiparticle nature.

There may be other conservation laws that we are not aware of. Each law is associated with one of the attributes of the particles or with the properties of our description of them. Since the present system of laws and attributes does not explain all the observed processes, we can surely look forward to other surprises.

THE PARTICLES

Particles Stable Against Decay Through the Strong Nuclear Interaction

We have considered the interactions among the particles and some of the peculiar features of the microworld. Now we shall meet the actors themselves. The organizational scheme for some of the particles shown in Figure 21 is comparable to Dmitri Mendeleev's Periodic Table of the

Elements, devised 100 years ago. In 1957 a young American physicist named Murray Gell-Mann proposed that the particles could be arranged according to a tabular scheme and that more particles would be found with the required characteristics to complete the chart.

During the last few years, Gell-Mann's chart has served the same function that Mendeleev's table did years ago. Undiscovered particles and their characteristics were predicted, sought after, and subsequently found. Gell-Mann's prophecy has now been fulfilled. In August 1963 the last predicted member of the chart—the anti-xi—was found.

Mendeleev's table contained no explanation for the observed periodicity in chemical behavior. Instead, it served as a great proving ground for all the atomic theories that were attempted during the following 50 years. (The quantum theory development of the original Bohr* atom successfully explained the Periodic Table many years after its conception.) In like manner, we now have organization schemes for the particles, but we still have no theory to explain why the particular schemes work and why particles have their particular values of mass and other attributes. All of the particles in Figure 21 are stable against decay in nuclear times of 10^{-23} second. Most of them are actually unstable but decay more slowly through the Electromagnetic Interaction and much more slowly through the Weak Interaction.

Two other particles, not included in the original scheme, are also stable against nuclear decay and have been included on the chart. These are the Ω baryon and the η^0 meson. The W particle of the Weak Interaction should also be included when more is known about it. There may yet be others.

To make sense of the table, first locate the familiar particles—the electron, proton, and neutron. Since the particles increase in mass from the bottom to the top of the table, the electron is near the bottom with a creation mass–energy of 0.51 million electron volts (Mev). The

*Described by Niels Bohr, Danish winner of the Nobel Prize for Physics in 1922.

neutron at 939.5 Mev is just slightly heavier than the proton. The difference between them is enough, however, to make the neutron unstable when it is by itself and not in a nucleus. It decays into a stable proton and two lighter particles.

Notice also that the photon, the agent of the electromagnetic field, is listed as a particle with mass zero. In the form of a radio wave, a chunk of electromagnetic radiation may not appear very much like a particle, but at the much higher frequency and energy of an X ray it behaves very much like one.

The chart has two major divisions vertically—particles and antiparticles. All of both kinds have been produced, and the antimatter is every bit as real as the matter. Three particles, the photon, the π^0, and the η^0, are placed on the dividing line. In effect, they act as their own antiparticles. They can do this because they are members of a class of particles, the bosons, which we must now distinguish.

There are four horizontal divisions, each with a name derived from the Greek.

The *baryons* (heavy particles) consist of particles like the proton. The *leptons* (light particles) may be thought of as the electron group. Within each group the particle *number* must remain constant. A new particle can be created out of energy but only if its antiparticle from the same group is created at the same time. (The particles of a group are assigned positive particle numbers while the antiparticles are assigned negative numbers.) No baryon can be created from energy unless an antibaryon is created at the same time. When an antibaryon is annihilated, it must take with it a baryon. The same is true for the lepton family. When a radioactive nucleus emits an electron (a beta ray), an antilepton must also be shot out—in this case an antineutrino.

The members of the other two classes, called *bosons*, obey no such conservation principle. There can be as many mesons or photons generated as there is energy available.

One interpretation of this difference is that the baryons and leptons are the *sources* of the interactions, or forces, and that particles of the other two classes are the *agents* of

these forces. We have already noted that the photon is the agent of the electromagnetic field and that Yukawa predicted the existence of an intermediate-weight particle—the meson—as the agent of the Strong Nuclear Force. We have since discovered that there are several kinds of mesons—the π (pi), K (kā), and η (eta). As we see in Figure 26, there are yet other meson combinations with even shorter lifetimes.

There is no agent of the Weak Interaction on the chart, but the prediction is that it should have a mass larger than that of the K-mesons and, necessarily, have mesonlike characteristics.

One is tempted to think of the heavier baryons as being compounds of the proton (or neutron) and mesons. However, at this point we are not even sure that protons or neutrons are "fundamental" particles. The stability of the proton may be almost accidental, and nuclear reactions may depend on the properties of lambda or sigma particles. As far as the nuclear forces are concerned, the proton and the neutron are the same particle with different states of electric charge. In some theories it is assumed that all of the baryons are essentially the same particle with different isotopic spins. Remember that there is no complete theory to explain these particles yet and many strange ideas are still being explored.

The lepton family presents even more puzzles. There seems to be no excuse for the existence of the heavy electron, called the *muon*. In almost every way it behaves like the electron except that its mass is 200 times greater! The muon shows up in the decay of the pi-meson, as can be seen in Figure 24. When the pi-meson decays, a neutral particle must be emitted in the direction opposite that of the muon in order to conserve momentum.

Since the same kind of thing happens in beta decay, it was assumed until 1962 that the neutral particle was the neutrino. In an experiment at the largest particle accelerator in the world, the Alternating Gradient Synchrotron (Figure 25) at Brookhaven, it was proved that the neutrino accompanying the muon is different from the neutrino accompanying the electron. Thus the strange difference be-

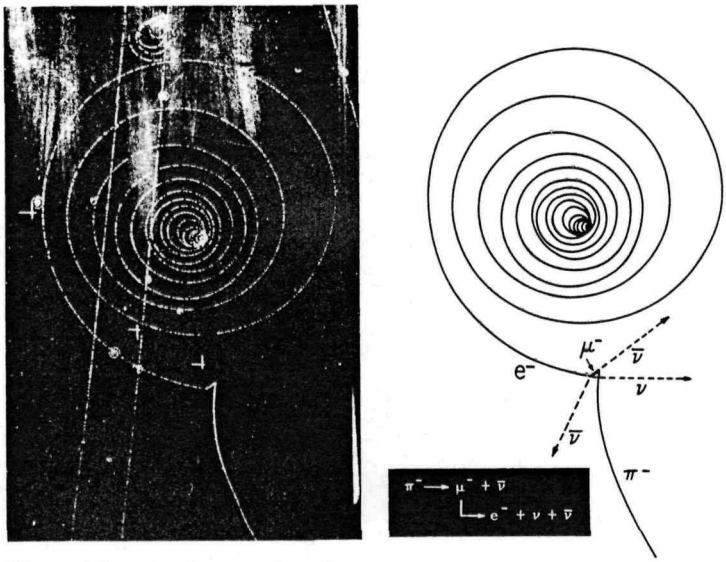


Figure 24 *The decay of a pi-meson.*

Courtesy Brookhaven National Laboratory

tween the electron and the muon becomes even more curious and, so far, is unexplainable.

Both kinds of neutrinos have been detected in their inverse process of colliding with material, in spite of the fact that their rate of interaction with matter is extremely

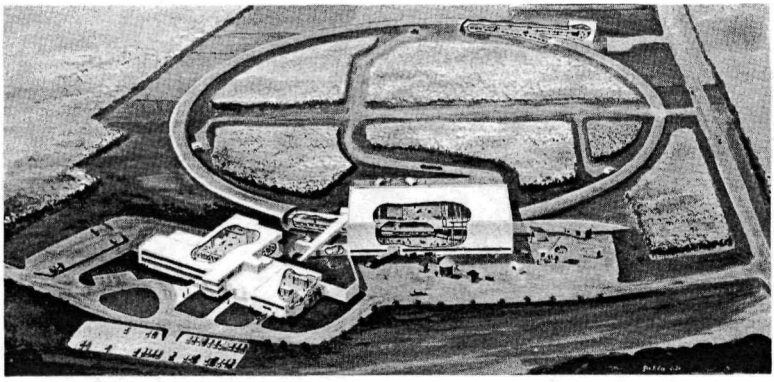


Figure 25 *The Alternating Gradient Synchrotron at Brookhaven National Laboratory, Upton, Long Island, New York.*

Courtesy Brookhaven National Laboratory

small. (In going through the whole earth, only one low energy neutrino in ten billion would suffer a collision.) Since the neutrinos have no electric charge, they are not subject to the Electromagnetic Force and can be affected only by the Weak Interaction. None of the leptons is subject to the Strong Nuclear Force.

Particles That Decay Through the Strong Nuclear Interaction

Even before all the stable and semistable particles of Figure 21 were discovered, a new type of event had been observed. In certain types of high-energy collisions, a particle was found which almost immediately decayed to a proton and a pi-meson. The lifetime of this temporary particle was only a little longer than the basic time of Strong Nuclear Interactions—10^{-23} second. Such a short time cannot be measured by observing the particle's flight in a track chamber. The path would not be much longer than the diameter of a nucleus.

The existence of the particle and its lifetime could be detected only by analyzing the tracks of its decay products. These showed that the proton and the pi-meson had moved as a single particle before breaking up. Similarly, when pi-mesons were shot through a hydrogen target at a particular energy, a large number were momentarily captured and then released again in all directions.

Since 1962 many such short-lived particles have been found. A partial list is given in Figure 26. Notice there appear to be particles composed of baryons and mesons and also combinations of only mesons. An immediate question is: Are these in any sense true particles, or are they just compounds of the more elementary particles? When the first proton–pi-meson combination was observed, most physicists thought of it as a resonance, or an "excited state" of the proton. Similar excited states of the atom had been measured early in this century. We do not think of the excited hydrogen atom just before it emits a photon as being a separate type of atom. On the other hand, it seems arbitrary to say that a particle which decays through the Electromagnetic or the Weak Interaction is a

SHORT-LIVED PARTICLES

List of Particles Unstable Against Fast (10^{-23} seconds) Decay Through Strong Nuclear Interaction

	Mass in Mev	Isotopic spin	Spin	Old names	Proposed nomenclature
Mesons	750	1	1	ρ (rho)	π (750, 1^-) (pi)
	782	0	1	ω (omega)	η (782, 1^-) (eta)
	881	$1/2$	1	K* (K star)	κ (888, 1^-) (kappa)
	1,020	0	1	φ (phi)	η (1,020, 1^-) (eta)
	1,250	0	2	F (ef)	η (1,250, 2^+) (eta)
Baryons	1,238	$3/2$	$3/2$	N* (N star)	Δ (1,238, $3/2^+$) (delta)
	1,385	1	$3/2$	Y* (Y star)	Σ (1,385, $3/2^+$) (sigma)
	1,405	0	—	Y* (Y star)	Λ (1,405, –) (lambda)
	1,512	$1/2$	$3/2$	N* (N star)	N (1,512, $3/2$) (N)
	1,520	0	$3/2$	Y* (Y star)	Λ (1,520, $3/2^-$) (lambda)
	1,530	$1/2$	$3/2$	Ξ* (xi star)	Ξ (1,530, $3/2^+$) (xi)
	1,660	1	$3/2$	Y* (Y star)	Σ (1,660, $3/2$) (sigma)
	1,688	$1/2$	$5/2$	N* (N star)	N (1,668, $5/2$) (N)
	1,815	0	$5/2$	Y* (Y star)	Λ (1,815, $5/2$) (lambda)
	1,920	$3/2$	$7/2$	N* (N star)	Δ (1,920, $7/2$) (delta)

Note that each of these particles represents a multiplet—a group of almost identical particles differing in the value of electric charge they carry. The number of particles in each multiplet depends on the isotopic spin. Λ (1,405—) is a singlet with isotopic spin 0 and electric charge 0; Δ (1,238, $3/2^+$) is a quadruplet of particles, one of which has electric charge of +2, another +1, another 0, and the fourth −1. Furthermore, all of these particles have antiparticles.

Figure 26

true particle and that, if it decays through the Strong Nuclear Interaction, it is a compound or an excited state.

Present theories view these interactions not so much as forces as routes by which particles can go from an initial state to a final one. For example, in the decay of the neutron to a proton, an electron, and an antineutrino, the route is the narrow one of the Weak Interaction (Figure 27). It is a two-way route since, if the energy balance were satisfied, a proton and an electron could produce a neutron and a neutrino.

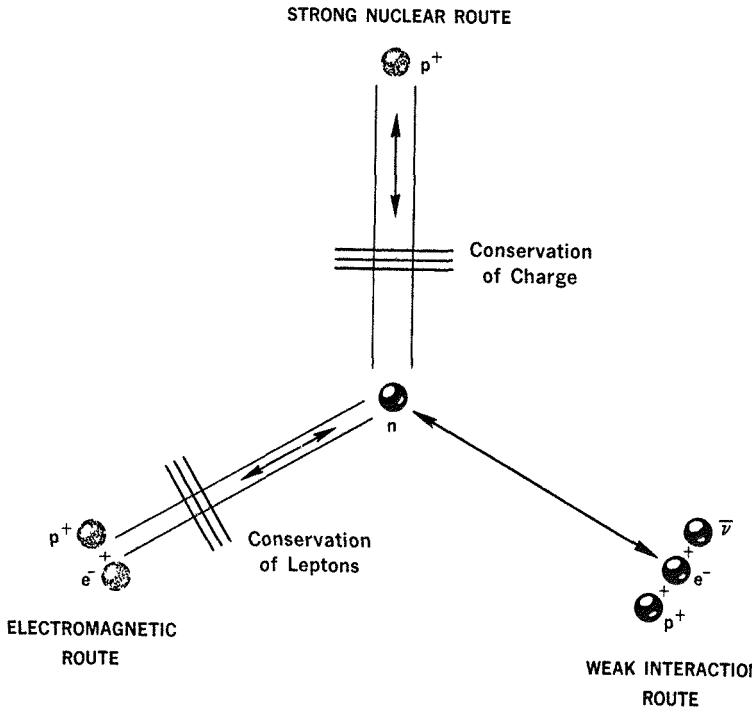


Figure 27 *Particles will transform into any combinations if linking routes are available and not forbidden and if energy permits.*

Which way the reaction goes depends on the available energy. In general, any particle will try to decay to a lighter combination. If the neutron could decay to a proton alone, the broad route of the Strong Nuclear Interaction would make the process go immediately. This is forbidden,

however, since electric charge would not be conserved. The Electromagnetic route is narrower than the Strong Nuclear by a factor of 100 but is still 10^{11} times wider than the Weak. By the Electromagnetic route the neutron could decay into a proton and an electron and so conserve electric charge. However, if this occurred, leptons would not be conserved since a single electron would be created where none existed before. The Electromagnetic route could not lead to a proton, an electron, and an antineutrino because the neutrinos are not affected by the Electromagnetic Force. Only the narrow route of Weak Interaction satisfies all the conservation laws and connects the necessary decay products.

The peculiar feature of the Strong Nuclear Interaction is that, since it so strongly connects many different combinations of baryons and mesons, any combination acts as if it were partially all the other combinations. A pi-meson, for example, can apparently exist momentarily as a baryon–antibaryon. Such temporary states can be found which will satisfy the conservation of electric charge, strangeness, spin, and everything except energy. Remember, however, that the Heisenberg Uncertainty Relationship allows energy fluctuations during very brief times.

This strange possibility is very useful in explaining many particle events. For example, the neutral pi-meson has no Electromagnetic Interaction and yet decays to two photons, which are the agents of the electromagnetic field. According to our model, this can occur because about 1% of the time the neutral pi-meson is a proton–antiproton pair. These annihilate each other, giving off two photons. Energy is conserved in the final state.

Under these circumstances the distinction between *source* and *agent* of the Strong Nuclear Interaction begins to fade. All that is important is the interaction itself which in some way gives rise to more or less stable resonances we call particles. Attempts are being made to build theories that will explain why particles exist with certain characteristics of mass, spin, etc., and not others. Although it may be possible to tie together the strongly interacting particles—the baryons and mesons—there is no indication that the leptons and photons can be explained in a

similar way. Obviously many mysteries remain. What is the nature of the Weak Interaction agent? Why are there two types of electrons—heavy and light—each with its own neutrino? What other particles may exist?

The key to some of these problems lies in even higher bombarding energies. New machines are being designed to produce energies ten times higher than are now available. A bold, and very expensive, program for the construction of such machines has been proposed by the President's Advisory Commission on Science and Technology. The results expected from the expenditure of several billion dollars, if this is authorized, may not be as dramatic as the exploration of space, and there is no expectation that more information about the Weak Interaction will yield any practical results. But then, there is no indication that knowledge about the far reaches of the solar system will ever be useful to man, either. And, out of four types of forces, only two are well understood. And man is a very curious creature!

APPENDIX I

THE TOOLS OF EXPLORATION

The exploration in the microworld requires, paradoxically, giant machines and instruments. The reason is clear when you consider that most of the particles must be created if they are to be examined. This means that their mass–energy must be supplied.

In practice, protons or electrons are accelerated to very high energy and then shot at a target of a chosen element. At energies above 100 million electron volts, 100 Mev, the nature of the material in the target is usually unimportant. The bombarding particles collide with the individual protons and neutrons in the nuclei and pay no attention to the atomic chemical (electron) structure. In an individual collision of a proton with a proton, some of the kinetic energy can be used to create the mass of the other particles (Figure 28).

Whether we picture the particle as already existing within the proton or neutron and being knocked out during the col-

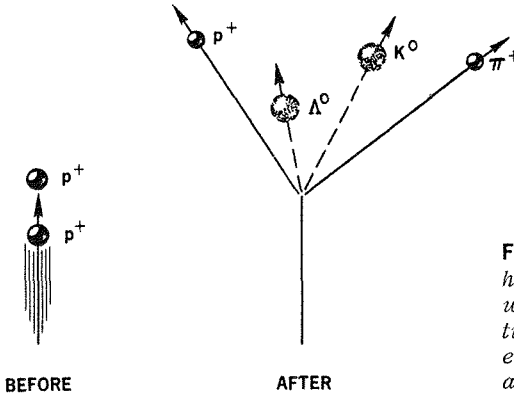


Figure 28 *Collision of high-energy proton with stationary proton turns some kinetic energy into mass of π^+ and K^0.*

lision or as being created during the process is a moot question. The point is that, without sufficient energy being provided, it cannot be freed.

The energy needed to create some particles, such as the antibaryons, is over two billion electron volts (2 Bev). The bombarding particle must have an energy much greater than that, and such energies can be provided only by very large accelerators. Brookhaven's Alternating Gradient Synchrotron (AGS) is shown in Figure 25. It is almost half a mile in circumference and can accelerate protons to 33 Bev.

The accelerators that produce energies over 1 Bev accelerate either protons or electrons, depending on the design of the machine. Most of these are circular machines, although two linear accelerators for electrons have achieved energies of over 1 Bev, and a very much larger linear machine is being built at Stanford University in California. In all these machines a group of particles is shot in at low energy and then is given repetitive electrical shoves as it passes through accelerating stations in the vacuum tank. Each group may contain as many as 10^{12} particles (one thousand billion).

In the circular accelerators, such as the AGS or Berkeley's Bevatron, the particles follow a racetrack path, which leads them past the same accelerating stations over and over again. The magnetic field in the channel constrains them to follow the circular orbit and also provides the necessary focusing to keep the particles from oscillating

too far from the center of the group. This magnetic field is weak at first since the particles have low momentum. As the particle energy increases, the magnetic field must increase, and also the accelerating frequency at the stations must become faster to keep pace with the more rapidly passing particles. After a million or so revolutions, the particles are directed out of the machine or onto a target.

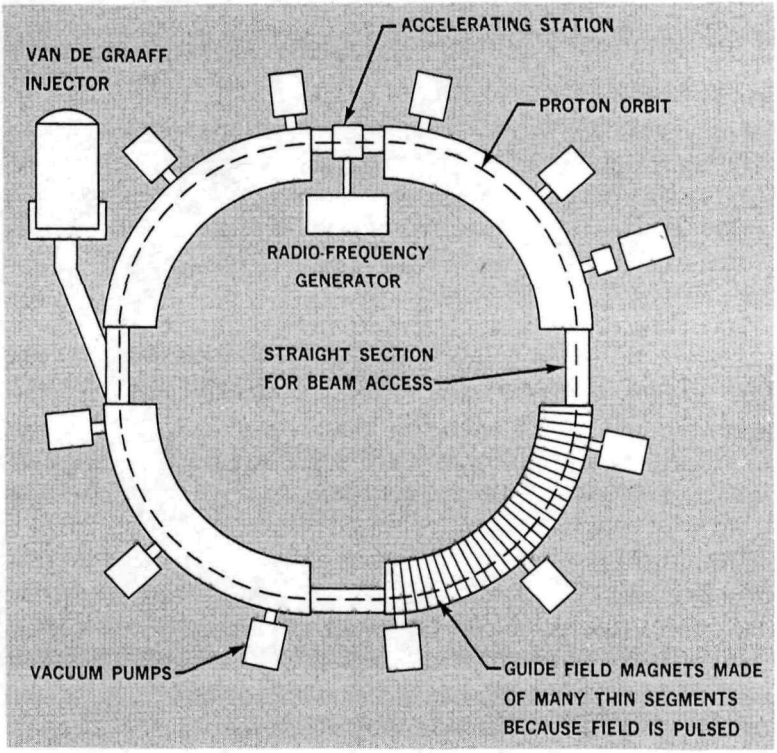


Figure 29 *Plan View of Brookhaven National Laboratory's 3-Bev Cosmotron.*

The whole cycle usually takes several seconds. The plan view of Brookhaven's 3-Bev Cosmotron in Figure 29 shows how the different components are arranged.

The particle reactions are detected with different types of counters, or their tracks are made visible with cloud chambers, bubble chambers, spark chambers, or photographic emulsions. In almost all cases the detection devices make use of the derangement produced by the fast

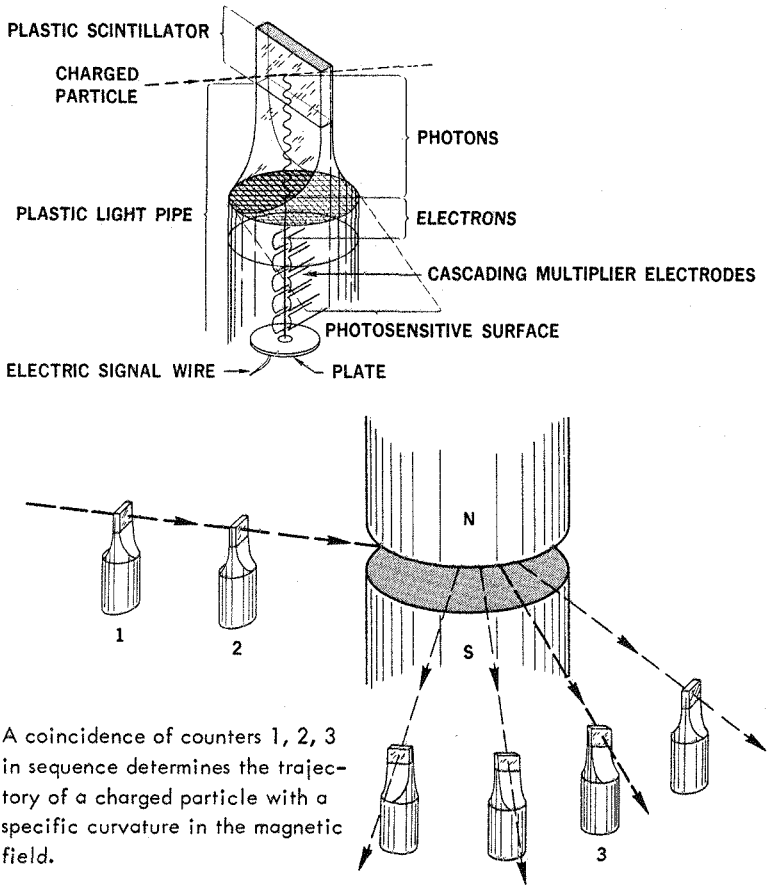


Figure 30 *Particle detection with scintillation counters.*

particles as they pass through the matter of the detecting agent. A charged particle rips electrons off the atoms through which it passes, leaving a trail of positively charged ions behind. As certain types of excited atomic or molecular systems settle back to normal by recombining with electrons, they release binding energy in the form of light. Photomultiplier tubes turn the light pulse into an electric pulse of much greater energy, and this can be recorded by electronic counters. Figure 30 shows the structure of a standard scintillator counter and illustrates a typical experimental arrangement. Such devices can record the

passage of a fast particle in less than one ten-millionth of a second. With the proper electronic circuitry, they can determine, with a precision of one-billionth of a second, whether or not two particles arrived at the same time.

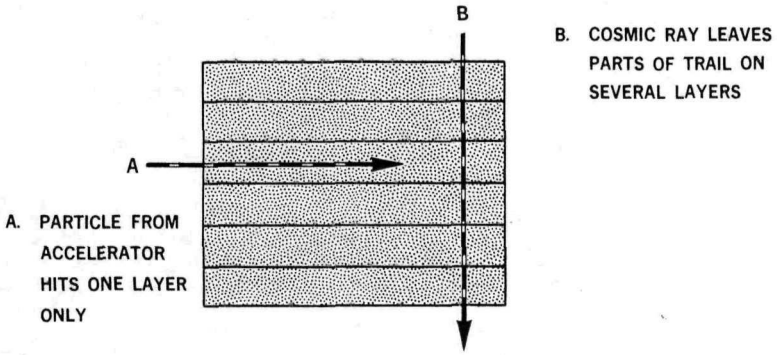


Figure 31 *Emulsion layers to detect particles.*

The ions produced by a charged particle can also serve as seeds for the growth of much larger effects. In a photographic emulsion (see Figure 31), for example, each silver atom freed from the silver iodide compound is the center on which a large grain or crystal of silver can grow during the photographic development process. The resulting trail of silver grains can be seen with the aid of a microscope.

In a cloud chamber (see Figure 32), a region of supersaturation is produced in a humid gas. This can be done

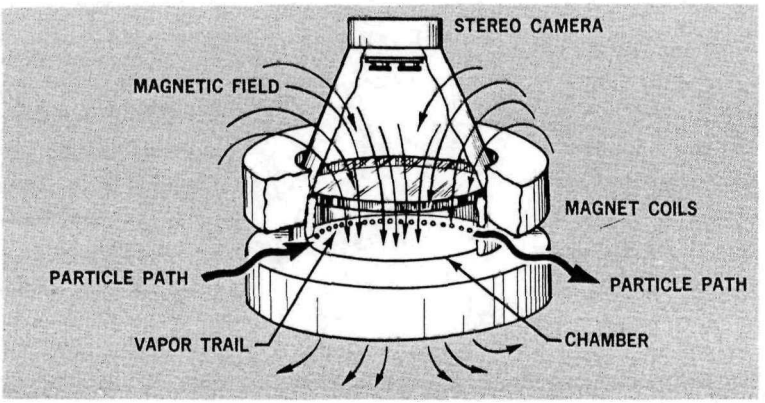


Figure 32 *Diagram of a cloud chamber.*

by a rapid expansion of the volume of the container to produce a rapid cooling of the gas, thus raising its humidity above 100% Droplets form on the ion trails; each ion is the seed for a droplet, which grows to visible size in less than one thousandth of a second. The trails are recorded with a camera.

Another form of cloud chamber is continuously sensitive. Warm vapor is released at the top of a container in which the temperature steadily decreases toward the bottom. As the vapor descends, it passes through a region of supersaturation. Fast charged particles passing through this region leave ion trails which turn to droplet trails.

Operation of the bubble chamber is very similar to that of the cloud chamber. Liquid in a container is kept almost at its boiling point. A sudden reduction in pressure in the chamber sends the liquid over the boiling point for that lower pressure. Boiling begins, however, only on the ions left by particles passing just at that moment. A bright light flashed into the chamber at that time illuminates the bubble trails so that they can be seen and photographed. The main advantage of the bubble chamber for high-energy research is that a liquid is from 100 to 1000 times as dense as the gas of a cloud chamber. Many more events can be seen in the liquid than in the same volume of gas.

Since 1961 many spark chambers have been developed for high-energy research. The structure of these can take many forms, but usually numerous metal plates are spaced a few millimeters apart in a noble-gas atmosphere (see Figure 33). Upon command of other counters, the voltage of every other plate is raised by 10,000 to 30,000 volts. Any ion trail existing between the plates serves as the leader for a lightning stroke — a spark jumping from plate to plate. These are photographed by cameras looking between the plates. The whole process takes only one-millionth of a second, and the chief advantage of the spark chamber is this small response time. The apparatus can lie dormant while millions of particles go through, and then, when outside counters determine that the right combination has been produced, the spark chamber can capture the rare event. Figure 34 is an example of a spark-chamber picture.

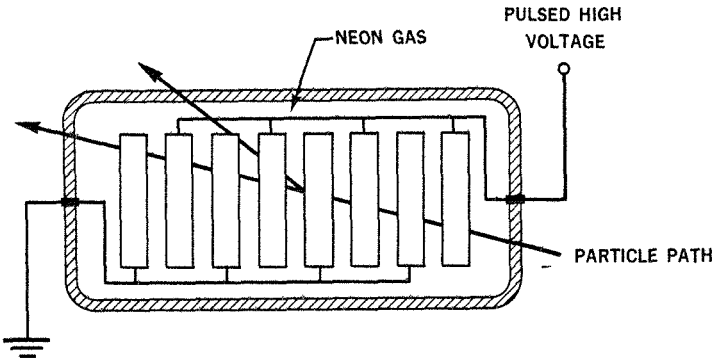


Figure 33 *Diagram of a spark chamber.*

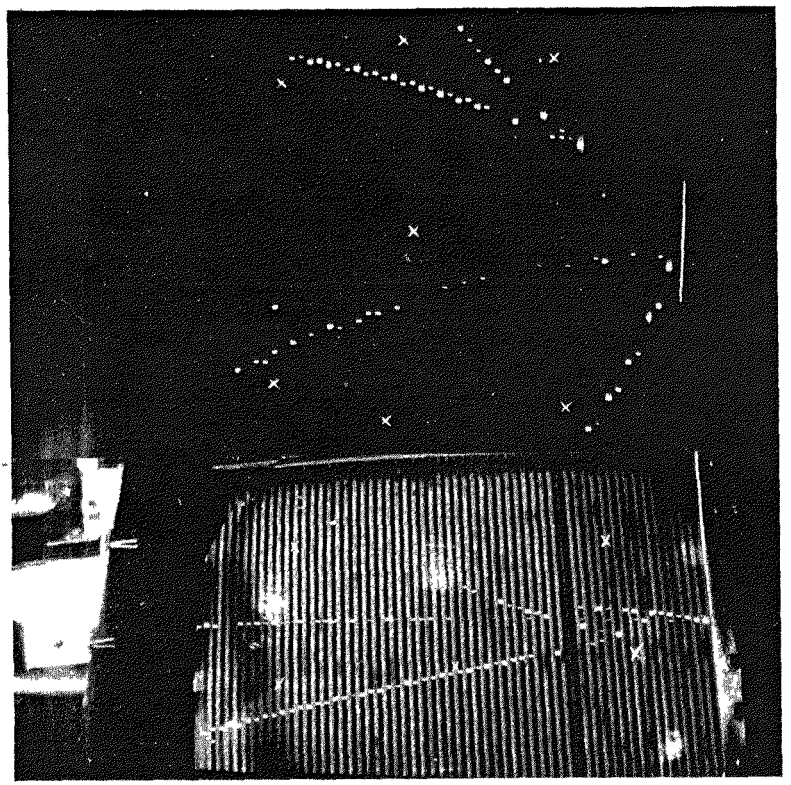


Figure 34 *Spark-chamber picture of Λ^0 and θ^0 decay.*

Courtesy Brookhaven National Laboratory

APPENDIX II

THE LANGUAGE OF THE MICROWORLD

It is important that we understand the names of the major features of the microworld, as used in Figures 3, 21, and 26 and throughout this booklet. Some of the nomenclature is given here for your ready reference. Other terms are explained in the text.

In Figure 21 we see that groups of particles have been classified as *bosons* and *fermions*, and also as *baryons*, *mesons*, and *leptons*. The word *hyperon* also appears, applied to several particles. Let us see what these and other terms refer to.

All elementary particles are classed in two groups, fermions and bosons. Two bosons can exist in the same energy state at the same time, but two fermions cannot; this fact is what differentiates between these large groups of particles.

A baryon is one of a class of *heavy* particles which includes protons, neutrons, hyperons, and cascade particles (or cascade hyperons). All free baryons heavier than a proton decay into a proton plus other end products.

A meson is a *medium*-mass particle which has mass greater than that of an electron and less than that of a nucleon (proton or neutron). There are several kinds of mesons: K-mesons, eta-mesons, and pi-mesons (or pions).

A lepton is one of a class of *light* particles which have no Strong Nuclear Interactions (explained in the text) and which include electrons, muons, and two kinds of neutrinos.

These three classes embrace many of the most important particles.

A hyperon is one of a class of baryons, heavier than nucleons (the constituents of atomic nuclei). There are several kinds of hyperons: omega hyperons, cascade hyperons (or xi-hyperons), sigma hyperons, and lambda hyperons. In other words, the different hyperons are four of the subclasses of baryons. There also are three subclasses of mesons, four subclasses of leptons, and two kinds of massless bosons.

In Figure 3 the particles are arranged in descending order of their masses (as measured by the energy needed

to create them). The different subclasses (such as omega hyperons), therefore, are groupings of particles by mass.

Other particle terms, such as lambda zero (Λ^0), refer to specific particles and their charges. Descriptive terms like "multiplet" refer to mesons and baryons which occur in families of states differing only in electric charge.

Greek letters are used as symbols for many of the particles. A bar over a particle symbol indicates that it is an antiparticle. A plus, zero, or minus superscript after a symbol indicates its charge.

Finally, notice in Figure 26 that the method of naming particles is still being revised. This is not surprising in view of the complex subject matter, the continuing discoveries, and the fact that theory to explain all this is still developing.

APPENDIX III

TRACKING THE PARTICLES

Throughout this booklet there are photographs showing particle tracks as they were formed in various kinds of counting chambers. The first of these is Figure 8 on page 11, also shown on page 56. To interpret these photographs, we need to keep the following facts in mind.

The motion of charged particles can be directed by electrical or magnetic forces. Charged particles are repelled by electrical charges like their own and so move away from them; they are attracted by opposite charges and move toward them. A charged particle in motion is influenced by a magnetic field; that is, negatively charged particles will circle one way in a magnetic field and positively charged particles the opposite way. Charged particles can be accelerated as they pass through an attracting electrical field, acquiring energy proportional to the difference of potential creating the field. This is what happens in an accelerator.

A charged particle (such as one from an accelerator) dissipates its energy as it passes through any material, including materials making up *photographic emulsions* and

the gases or liquids in *cloud chambers, bubble chambers,* and *spark chambers.* The particle may pass close enough to an atom (of the medium it is traversing) to ionize it by knocking off one of the atom's electrons. This leaves the atom available to serve as a center for formation of a drop in a cloud chamber, as a boiling center in a bubble chamber, or as part of a pathway for an electric spark in a spark chamber. (Ionization, of course, affects only a tiny fraction of the atoms in the medium.)

The charged particle may also exchange energy with the ion in an elastic collision. No kinetic energy is lost in such a case, but the particle will alter its course and the ion also will be set in motion.

Alternatively, the accelerated particle may either come very close to an atomic nucleus or hit it. If the energy of impact is greater than the forces holding the nucleus together, the target nucleus may break up into other particles—protons, neutrons, and various mesons—which may leave tracks, too. (Some of the energy also may emerge as electromagnetic radiation.)

The charged particle may be an unstable one, in which case it will decay into other particles, which then continue in motion through the chamber. Some of these may decay, too. Whatever happens will be recorded in the chamber. (Uncharged particles, such as neutrons, neutrinos, lambda zeros, etc., leave no trails; but, when they strike something else or decay into charged components, the new product *will* leave trails.)

To read a track-chamber photograph, then, we watch for ionization trails which suddenly change course or which branch into two or more trails. (Most of the parallel trails are caused by particles merely passing through, knocking off an occasional electron as they go by.) Each point of changed direction or branching indicates where a collision or a decay has taken place; the trails beyond that point are left by particles created in a collision (or by decay) or by particles altering their course because of it. Curved trails indicate the presence of a magnetic field in the track chamber. When an electron is removed from an atom, for example, the magnetic field winds the electron up in a tight little spiral.

Physicists determine the mass and energy of resulting particles by measuring the width, density, length, and direction of the trails, and from these they identify the particles.

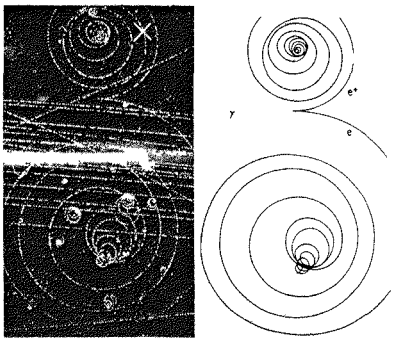
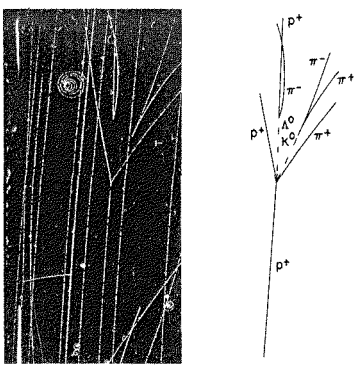


Figure 8 (reprinted here for your convenience) shows an example of "pair creation", or the conversion of energy to matter. A gamma ray (leaving no track) with energy greater than 1 million electron volts (entering the photograph from the left) passed close to the nucleus of an atom. It converted into an electron and a positron; since the gamma ray had no charge, its products also had to add up to zero—hence the creation of oppositely charged particles. Pair production is one of the most common processes by which a neutral high-energy photon produces charged particles.



Or consider Figures 14 and 15 on page 21, reproduced here. A proton (p^+) entered a bubble chamber from the bottom and collided with the nucleus of an atom of the liquid in the chamber, and two neutral particles, a K zero (K^0) and a Lambda zero (Λ^0), were formed. Each of these traveled upward for some distance, leaving no trails. Then each decayed into two charged particles that did leave trails, the K^0 decaying to a pi plus (π^+) and a pi minus (π^-) and the Λ^0 decaying to a proton (p^+) and a pi minus (π^-), all four of which did leave trails.

Now let us follow a somewhat more complicated event, production of a negatively charged omega-meson (Ω^-) as photographed in the 80-inch liquid-hydrogen bubble chamber at Brookhaven (Figure 35). The photograph and sketch show

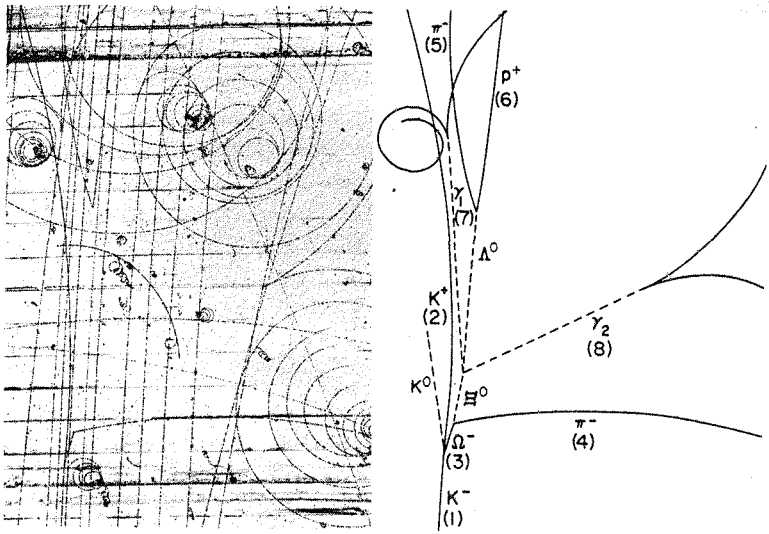


Figure 35 *Bubble-chamber photograph and sketch showing production of negatively charged omega-meson (Ω^-) by interaction of a negative K-meson (K^-) with a proton.*

Courtesy Brookhaven National Laboratory

what happened when a beam of K minus (K^-) mesons, produced by the Alternating Gradient Synchrotron, entered the bubble chamber. Track 1 shows an incoming K^-, moving upward from the bottom. It collided with an unseen, stationary proton in the liquid hydrogen with the resultant production of a neutral K-meson (K^0), a positive K-meson (K^+, track 2), and the negative omega-meson (Ω^-, track 3). The Ω^- decayed, after a lifetime of about one ten-billionth of a second, into a neutral cascade hyperon (Ξ^0), and a negative pi-meson (π^-, track 4). The Ξ^0 decayed into a neutral lambda hyperon (Λ^0) and a neutral pi-meson (π^0), not shown, which immediately decayed into two gamma rays (γ_1 and γ_2, tracks 7 and 8), which in turn converted to a positron–electron pair (e^+ and e^-). The neutral lambda hyperon (Λ^0) traveled a few centimeters and then decayed into a negative pi-meson (π^-, track 5) and a proton (p^+, track 6).

As we study such track-chamber photographs, remember that we are interested in particles which make up the microstructure of matter; the trails are merely a means of studying them.

SUGGESTED REFERENCES

Books

The following books are intended for readers who do not have intensive scientific background; most are appropriate for readers who have had some high school science courses.

The Neutron Story (Science Study Series), Donald J. Hughes, Doubleday & Company, Inc., Garden City, New York, 1959, 158 pp., $0.95 (paperback).

The Restless Atom: The Awakening of Nuclear Physics (Science Study Series), Alfred Romer, Doubleday & Company, Inc., Garden City, New York, 1960, 198 pp., $0.95 (paperback).

Knowledge and Wonder (Science Study Series), Victor Weisskopf, Doubleday & Company, Inc., Garden City, New York, 1962, 222 pp., $4.95 (hardback), $1.45 (paperback).

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Cosmic View: The Universe in 40 Jumps, K. Boeke, John Day Company, New York, 1957, 48 pp., $3.75.

The following group demands more of the reader, although the material is well within the reach of anyone who is taking high school physics.

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Annual Reviews of Nuclear Science, Annual Reviews Inc., Palo Alto, California.
Progress in Elementary Particle and Cosmic Ray Physics, Interscience Publications, New York.
Progress in Nuclear Physics, Pergamon Press, New York.

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C., and other AEC film libraries.

Atomic Research: Areas and Development, 12½ minutes, sound, black and white, 1953. Produced by Coronet Films, Inc. This nontechnical film illustrates three lines of research: energy,

atomic structure, and by-products. It shows how the structure and particles of atoms are studied with particle accelerators.

The High Energy People, $5\frac{1}{4}$ minutes, sound, color, 1963. Produced by AEC's Argonne National Laboratory. The automatic cameras that photograph the tracks of subatomic particles are explained, and the photographs themselves are analyzed. The Zero Gradient Synchrotron is also described.

Of Men and Matter, 29 minutes, sound, color, 1963. Produced by AEC's Brookhaven National Laboratory. A physicist explains that such machines as the Alternating Gradient Synchrotron are necessary for studying fundamental particles and the forces within the atomic nucleus that are the basic components of all existing matter. An experiment is shown in which the particle beam's interactions with the target nuclei in a bubble chamber are photographed. Analysis and scanning of the photographs are also illustrated.

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