

THE ELEMENTARY PARTICLES OF MATTER

by Murray Gell-Mann

All matter everywhere is composed of particles, each of which has identical properties throughout the known universe. As far as we can tell from the light from the most distant galaxies, electrons there obey the same laws that they do in our laboratories on the earth. So, presumably, do the other particles. The laws of these elementary particles, supplemented by the laws of the cosmos, underlie all the laws of natural science—first those of physics, then those of chemistry, geology, biology, astronomy, and all the others. We humans are made up of these same particles. One would like to find a simple and unified description of these elementary building blocks, but so far that unification has eluded us. For the moment we must still divide the subject of elementary particles into a few pieces which we investigate separately.

One way to divide the subject is to discuss four kinds of force, which are presumably responsible for all natural processes. Two of them have been familiar for a long time—gravitation and electromagnetism. Gravitation, understood first by Newton and then in an improved way by Einstein, is a long-range force of *very* small strength. To express its strength in natural units, we would have to write a fraction—one divided by a number written as 1 followed by 40 zeros (10^{-40}). Electromagnetism is also well understood and also a long-range force. Its

MURRAY GELL-MANN. *Caltech professor of theoretical physics, this month becomes the first Robert Andrews Millikan Professor of Physics. This new chair has been established by the board of trustees and is named in honor of the noted physicist and chairman of the executive council of the Institute from 1921 to 1945. "The Elementary Particles of Nature" has been adapted from an address Gell-Mann delivered at the Institute's 75th Anniversary Conference on October 25.*

strength is very much greater than that of gravity and can be described by a dimensionless parameter of about 1/100.

Then there are the two forces or interactions discovered in the 20th century that are responsible for subnuclear processes—the weak interaction, which leads to certain kinds of radioactive decay; and the strong interaction, which is responsible for the binding of the atomic nuclei. These are both very short-range forces with a range less than or equal to the size of an atomic nucleus—i.e., 10^{-13} centimeters, which is very much smaller than the size of an atom. At distances beyond that, these forces die away to almost nothing. The strong interaction, as its name indicates, is very strong indeed; on the scale of strength we are using, its strength is 1. The weak interaction is much weaker. An exact description of its parameter of weakness is not so easy to give, but a rough value is 1/10,000,000.

Microscopic physics is described by a magnificent and confusing discipline called quantum theory. Although none of us has fully understood it, quantum theory has been perfectly successful up to the present time. According to quantum theory, forces in general are expected to be transmitted between the objects they affect by means of a particle that serves as a carrier. The photon is the carrier, or quantum, of electromagnetism. This has been known for a long time. In the case of gravity, we theorists believe there must be a similar carrier called the “graviton,” but no one can figure out any way, with present technology, of doing an experiment to find it. Thus the graviton remains a hypothetical particle.

In the case of the weak interaction, we are not sure whether there has to be a carrier or not, because the force might be of zero range, making the idea of a carrier particle unnecessary. However, people continue to look for such a carrier or quantum of the weak interactions (sometimes called X), although they have not yet been successful. In the case of the strong interaction, the subject of a carrier is more complicated, and to introduce that topic let me first briefly discuss the other interactions.

There are some particles that are unfortunate enough not to participate in the strong (or nuclear) interaction. One group of these particles consists of the “leptons,” including the electron and neutrino. The electrons in an atom, particularly a heavy atom, spend a great deal of their time inside the atomic nucleus. But while they are there, they do not feel the nuclear force, whereas the nuclear particles feel it very strongly. The electrons pass right through and feel only the electrical force of the nucleus.

The neutrinos do not even have electrical inter-

actions. The electron e^- has an electric charge, but the neutrino is electrically neutral and has neither strong nor electromagnetic interactions—only the weak interactions. In “An Explanatory Statement on Elementary Particle Physics,” in *American Scientist*, M. A. Ruderman and A. H. Rosenfeld wrote: “Every second, hundreds of billions of these neutrinos pass through each square inch of our bodies, coming from above during the day and from below at night, when the sun is shining on the other side of the earth.” This inspired John Updike to write:

COSMIC GALL

Neutrinos, they are very small.
They have no charge and have no mass
And scarcely* interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.**

*The original reads “And do not interact at all.” This change is made by scientific license.

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Among the leptons we encounter a fundamental principle of relativistic quantum mechanics confirmed by all experiments up to the present time: that there is a symmetry of nature between particles and anti-particles. And so the leptons have their corresponding anti-leptons, e.g., the anti-neutrino and the positron. (The positron was discovered by Caltech’s Carl Anderson some 34 years ago.)

The strongly interacting particles also have anti-particles, which in most cases are different from the particles themselves. In any case, there is a perfect particle-anti-particle symmetry—provided, of course, that you make the anti-particles run backwards in space and time when you are performing the symmetry operation.

The so-called “hadrons” (which include mesons and baryons) are the particles (unlike leptons) that *do* possess the nuclear or strong interaction. Very familiar hadrons are the neutron and proton, which are popularly described as the building blocks of atomic nuclei. Their anti-particles, the anti-neutron

and anti-proton, have been discovered in the laboratory recently. If you replace protons by anti-protons, neutrons by anti-neutrons, and electrons by positrons in ordinary matter, you can build up so-called anti-matter. For every object you can make a corresponding anti-object. Such anti-objects behave in very much the same way, in an environment of other anti-matter, as ordinary objects do with respect to their normal background of matter. However, if the object and the anti-object are brought into contact with each other, they annihilate with a burst of energy. This has given rise to another poem, by the physicist Harold P. Furth.

PERILS OF MODERN LIVING

A kind of matter directly opposed to the matter known on earth exists somewhere else in the universe, Dr. Edward Teller has said . . . He said there may be anti-stars and anti-galaxies entirely composed of such anti-matter. Teller did not describe the properties of anti-matter except to say there is none of it on earth, and that it would explode on contact with ordinary matter.
—San Francisco Chronicle

Well up beyond the troprostrata
There is a region stark and stellar
Where, on a streak of anti-matter,
Lived Dr. Edward Anti-Teller.

Remote from Fusion's origin,
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from Earth.

Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.*

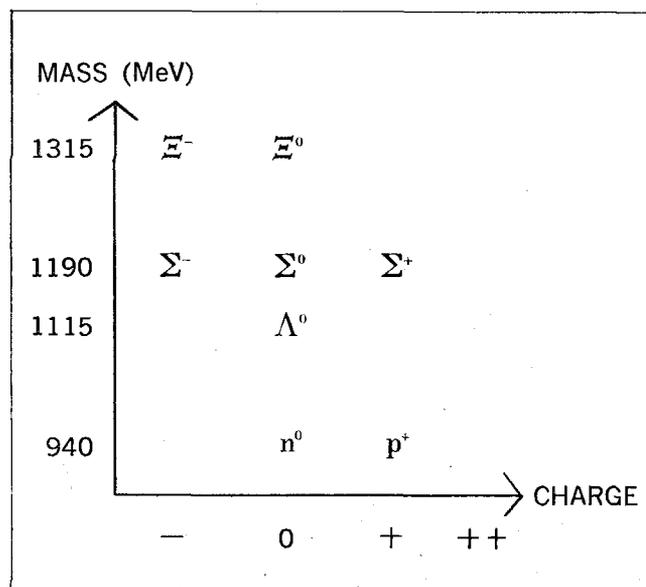
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Having presented this vivid picture of the distinction between matter and anti-matter, we can look at all the hadrons and try to arrange them by the value of a number A, which in elementary physics is called the atomic mass number. In elementary particle work it is often called the baryon number. The bookkeeping of A in nature seems to be very strict. As far as we know, the total A must agree exactly on both sides of any reaction. We can assign numbers A to the various nuclei: For example, the famous U^{235} and its excited states have an A of 235. The deuteron, or heavy hydrogen nucleus, usually pictured as consisting of a neutron and proton, is assigned $A = 2$. The neutron, proton, and all other so-called baryons, such as the particles Λ , Σ , Ξ , are assigned $A = 1$. Likewise, there

are the anti-baryons: anti-neutron, anti-proton, anti-lambda, which have $A = -1$. The anti-deuteron, which has actually been produced in the laboratory, has $A = -2$. And correspondingly, we could, given enough time and energy, make anti- U^{235} with $A = -235$. In the middle position, we have particles called mesons which have $A = 0$. The anti-particles of mesons are also mesons, and in some cases a particular meson is its own anti-particle.

Of all these hadrons, or strongly interacting particles, that participate in the nuclear force, which are the basic building blocks? What are they all made of? Virtually nobody in the business believes the popular tale that neutrons and protons are elementary building blocks, although this legend persists in textbooks. It does not appear that there is anything particularly elementary about the neutron and proton. They are simply the lowest energy states of an enormous set of baryon levels, of which some hundred are now known. There is no reason to believe that any one of these is any more fundamental than the others. The neutron and proton, because they are the lowest and most stable states, are the most conspicuous ones in our experience.

The baryon states, including the neutron and proton, come in families and super-families, with a beautiful and simple structure. For example, we now know that the neutron and proton are two members of a super-family of eight particles, illustrated below. Here each particle is represented by

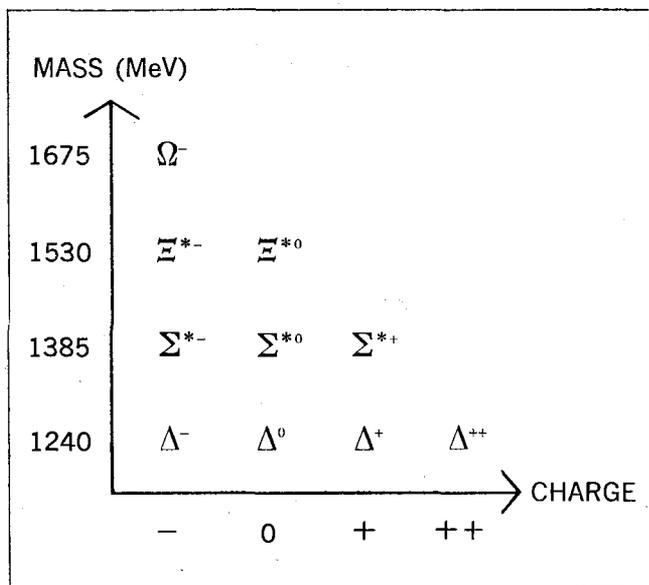


BARYON OCTET, $J = 1/2^+$

a point on a graph which has electric charge as its horizontal axis and the mass of the particle in units of MeV as its vertical axis. Each of these particles has the same angular momentum, one-half of the unit of angular momentum ($J = 1/2$). Each of them

is also characterized by the value of a certain peculiar number called parity, which is either plus or minus and which, for these baryons, is plus. Within the super-family of eight are smaller families, for example, the neutron and proton at practically the same energy, 940 MeV. Their energies differ by only about 1 MeV, and they form what is called a doublet. Higher, there is the Λ —a neutral baryon at 1115 MeV; then a triplet—the three Σ 's at about 1190 MeV, differing among themselves by a few MeV; then the Ξ doublet at 1315 MeV. But all of these together form the super-family, with its very large mass separation of a few hundred MeV. Within the super-family, the masses of the families obey a certain simple relation.

In another super-family, shown below, the mass



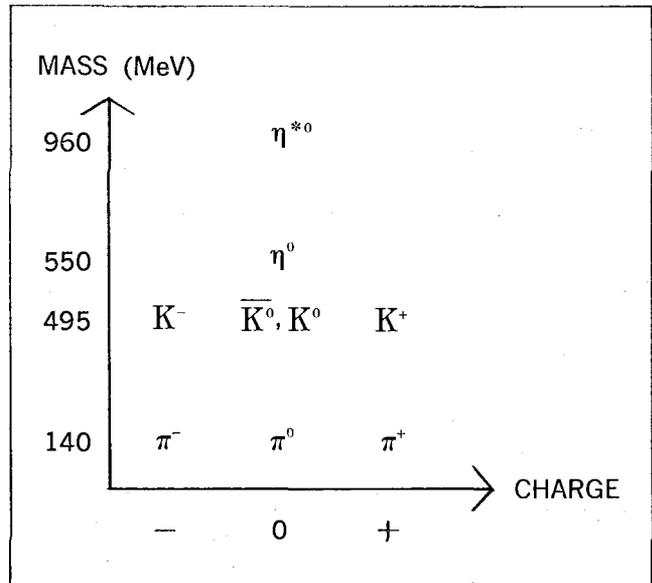
BARYON DECIMET, $J = 3/2^+$

relation is even simpler. This set of baryons has $3/2$ units of angular momentum ($J = 3/2$) and again parity plus. The members of the quartet at the bottom have about the same mass of 1240 MeV and electrical charges ranging from -1 to $+2$. Just above is another set of sigmas, in this case, excited sigmas, Σ^* , forming a triplet with charges -1 , 0 , and $+1$. Higher up, there is a Ξ^* doublet with charges -1 and 0 . Still higher is a singlet, Ω^- , with a negative charge.

The mass relation here is extremely simple. The mass spacings are all the same—about 145 MeV between each family and the next. As the number in the family goes down from 4 to 3 to 2 to 1, the masses go up in steps of 145 MeV. Both these patterns—the eightfold pattern above and the tenfold pattern here—were actually predicted by a theoretical method called approximate symmetry. We succeeded in predicting that the families in the decimet

would be equally spaced; so when the first two were found, it was possible to predict the next two—the Ξ^* and the Ω^- . The Ξ^* was found at once, but the Ω^- has some very peculiar properties, and people doubted that it would, in fact, exist. After a long, expensive, and agonizing search, it finally turned up at the Brookhaven National Laboratory with exactly the predicted properties.

The mesons, likewise, fall into families. The lowest set (below) is a bunch of mesons with zero



MESON OCTET AND SINGLET $J = 0^-$

units of angular momentum and negative parity. The fairly familiar pions, π , are at the bottom, a triplet at 140 MeV. Above are two doublets, K^- , K^0 , and their anti-particles, at 495 MeV. Above these are a singlet and another singlet. The whole pattern forms two super-families, an octet and a singlet, made up in turn of families: a triplet, two doublets, a singlet, and another singlet. Here the charges range from -1 to $+1$. As we see, the familiar π mesons are once again just three members of a much bigger set. And, as with the baryons, our super-family of eight plus one is accompanied by many other super-families lying higher in mass and with different values of the angular momentum and parity. Hundreds of meson and baryon levels are now known. The neutron and proton are simply the lowest of the baryon levels, and the pions are simply the lowest of the meson levels. So when you read in the newspapers that some very clever experimentalist has discovered 12 more elementary particles, you will know what he means. Now, having agreed that there is nothing special about the neutron and proton, we are left with the question, "What are these hadrons in fact made of?"

There are two current theoretical hypotheses—

which are not necessarily contradictory. One idea, and it seems a very promising one, is the so-called bootstrap hypothesis: that the hadrons are made up out of each other, so that none of them is particularly fundamental. Here we have a so-called democratic theory of hadron structure; every hadron level is as good as any other hadron level. I can give a crude description of how this situation comes about. If you take a baryon and an anti-baryon and you allow them, in the sense of quantum mechanics, to exchange a meson, then the meson acts as the carrier of the strong interaction in the same way that the photon acts as the carrier of electromagnetism. In that way, a force is generated between the baryon and the anti-baryon—the baryon and the anti-baryon attract each other, forming bound systems. And the bound systems are just mesons—the same mesons that generated the force responsible for the binding. The meson, then, is both the carrier and the bound state. It makes itself, and we see the bootstrap mechanism at work.

In the same way, the baryon is made of itself and a meson, exchanging a baryon to make the force. Now, in fact, if you try to consider the picture more accurately, you find that *all* hadrons are exchanged—that they make forces among all hadrons, that all hadrons bind to all other hadrons to make, as their bound states, all the hadrons. That is the bootstrap idea. It seems very promising, but it is rather difficult to use for detailed calculations. So far most of the calculations have given qualitative results; that is, they have shown that things might work more or less this way. They have not given a clear picture of exactly how things come out numerically.

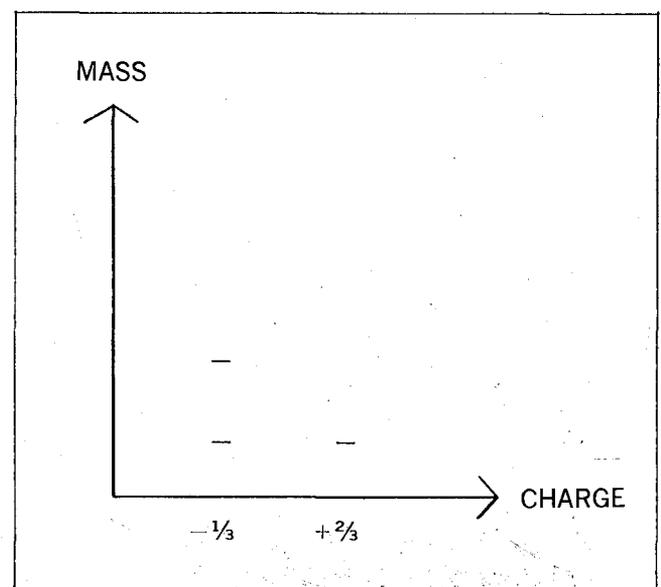
Another and far crazier picture, however, gives fairly accurate numerical results and predicts those patterns of hadron families that we showed before. This is the notion that hadrons are made of “quarks” and “anti-quarks.” But what *is* a quark? A quark is a very peculiar particle with an *A* or atomic mass number of $1/3$ and a charge of $+2/3$ or $-1/3$ (in the same units that we were using before). There are three kinds of quarks: one with charge $+2/3$ and two with charge $-1/3$. (One possible derivation of the name—scholars are already disputing this, some assuming it comes from the German word for rotten cottage cheese—is from the heading of a page in *Finnegan’s Wake* where Humphrey Chimpden Earwicker rolls over in his sleep to hear a clock strike and the text says, “Three quarks for Muster Mark.”)

As we see at the right, a doublet and a singlet are put together to make a system of three quarks. Of course, there are equally hypothetical anti-quarks with the opposite pattern of charges—a $-2/3$ and $+1/3$ doublet and then a singlet with $+1/3$. It turns

out, strangely enough, that if you put such quarks together, the combinations look very much like the pattern of observed baryons and mesons. Here is the recipe for doing so: you make the meson states by putting together one quark and one anti-quark, and you make the baryon states by putting together three quarks. We can illustrate, without going into mathematical detail, a little bit of how this works.

Suppose we look back, for example, at the baryon decimet. Remember that the hypothetical quarks are charged like this: $+2/3$, $-1/3$, and $-1/3$. If we put together three of them, we expect the charges of the combinations to range from $+2$ to -1 . And indeed this is what the baryons do.

Another point is that the quark singlet is higher in its mass than the doublet by a certain amount. So we expect that as we move from the larger charge multiplets, whose charges extend far to the right, to the smaller charge multiplets, the mass of the multiplets should increase regularly by this difference. And that is exactly what happens. For example, the low-lying quartet of baryons is made of three of the lighter quarks. The baryon triplet is made of two of the light quarks and one of the heavy quarks, while the baryon doublet is made of one light and two heavy quarks. Finally, the baryon singlet is made of three of the heavy quarks. The heavy quark has a charge of $-1/3$, so three of them gives us a charge of -1 in agreement with the heaviest baryon, Ω . This is just one illustration of the many simple properties of the meson and baryon systems that we get from studying the quarks. One completely crazy prediction, for example, which not even I believed at first, is that because the baryon is made up of three quarks and the meson is made up of a quark and an anti-quark



HYPOTHETICAL QUARKS, *q*

(that is, essentially 2), the ratio of baryon-baryon to meson-baryon scattering probabilities at very high energy ought to be 3 : 2. And, in fact, it is approximately 3 : 2. In many ways the quark structure seems to explain in detail the properties of the baryon and the meson systems of levels.

Are quarks actually real objects? My experimental friends are making a search for them in all sorts of places—in high-energy cosmic-ray reactions and elsewhere. A quark, being fractionally charged, cannot decay into anything but a fractionally charged object because of the conservation law of electric charge. Finally, you get to the lowest state that is fractionally charged, and it can't decay. So if real quarks exist, there is an absolutely stable quark. Therefore, if any were ever made, some are lying around on the earth. One atomic spectroscopist friend of mine calls me up, sometimes at midnight, to report his progress in a search for quarks in sea water. He has electrolyzed a huge amount of sea water to look for characteristic atomic levels of quark atoms. He thought he found one once, but it turned out to be an unknown line of tungsten. Since then he has decided that the chemical properties of real quark atoms—if they exist—would be very strange indeed. And since most things with curious chemical behavior in the ocean eventually are eaten by oysters, he is grinding up oysters and looking for quarks in them. He has not yet seen any, nor have any been found at very high energies in cosmic rays. So we must face the likelihood that quarks are not real.

Actually that is just as well; mathematical quarks are even easier to work with than real ones, because certain restrictions imposed by the reality of the particles can be dispensed with. And working with mathematical quarks, we can begin to make a fairly satisfactory theory of the detailed properties of meson and baryon levels.

If the quarks turn out, in fact, to be mathematical, then there is nothing to prevent the quark hypothesis from being equivalent to the bootstrap hypothesis. In other words, it is possible that the hadrons actually make up one another, according to the bootstrap mechanism, with forces coming from the exchange of hadrons—but when you work out in detail the properties of hadrons so formed, they will turn out to look as if they are made of quarks. At the present time, this seems a very likely state of affairs—both hypotheses right and equivalent. It is also possible, of course, that they are equivalent and both wrong—or inequivalent and both wrong. However, if it turns out that they are equivalent and one is right and the other one is wrong, we will probably be in trouble.



William Shakespeare's
will said:

"I give unto my wife
my second best bed
and its furnishings."

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