

The Strongest Force

This article by one of the co-discoverers of 'the eightfold way' of classifying strongly interacting particles, first appeared in 'Science Year 1968' and is reproduced here by kind permission of the publishers.

Yuval Ne'eman

by K. Unser. It has two channels, one for high and one for low frequencies, each with its own beam current transformer, and the channels are coupled in such a way that there is an automatic and continuous transition between the two to cover the whole range.

Beam current transformers for monitoring fast ejected beams have been developed by S. Battisti and R. Bertolotto. (At the synchro-cyclotron, R. Hohbach and S. Mango have achieved monitors of high sensitivity — down to about $0.5 \mu\text{A}$ — for the extracted proton beam.) The particular problem with ejected beams is the low beam current and an accurate device for slow ejected beams with a long spill-time has not yet been operated.

More difficulties come in when faced with the problem of monitoring the beam in storage rings. The aim is to provide a monitor for the ISR which will be capable both of measuring the total stacked beam current (with values up to 20 A circulating for many hours) and which will also be sensitive to small changes, so that the addition of an extra pulse (say 50 mA) from the PS during the stacking process can be monitored, and so that any beam losses can be detected. A paper on this work by Unser entitled 'Beam Current Transformer with D.C. to 200 MHz Range' was read at the 1969 Particle Accelerator Conference at Washington on 7 March.

The response of the monitor is extended to the d.c. condition (to measure the steady stacked beam in the ISR) by adding a magnetic modulator to the system already used on the PS (which measures the rapid changes). It consists of a pair of toroids which are excited by an auxiliary oscillator in opposite senses so that their signals, in a winding around both toroids, cancel. When a beam passes through, it introduces an asymmetry giving an output signal proportional to the current.

A prototype has given very encouraging results. It has been tested up to currents of 20 A and over a wide frequency range down to d.c. The accuracy was about 0.01 %.

When that visionary, Jules Verne, described the launching of the first manned space flight in his science fiction novel 'From the Earth to the Moon' in 1865, he calculated the height of Captain Barbicane's monstrous gun, the 'Columbiad', at 880 feet. When the gunpowder that filled a quarter of this gun was ignited, the space capsule, in an earth-shattering blast, shot instantly to the 36 000 foot-per-second velocity required to escape the earth's gravity. It was a jolting beginning to a remarkable lunar voyage.

In 1968, Verne's prophecy has become reality. Men of another century were constructing the Saturn V moon rocket, the most powerful machine ever built, to send an Apollo spacecraft soaring to the moon. To overpower gravity's enormous resistance, the Saturn's engines burn almost 4 000 gallons of fuel and oxidizer every second.

Man has thus learned how to overcome gravity — the gross force of all the earth's atoms. But within each small atom, there is a much larger force — electromagnetism. Imagine that tiny rocketeers living within an atom wished to launch a negatively charged electron against the electromagnetic pull of its positively charged atomic nucleus. They would need 10 000 times more fuel than the amount needed to lift a single electron from the earth to the moon. To further illustrate the strength of this force, imagine that a Space Age imp had removed all the electrons from only one-tenth of a cubic millimeter of the Apollo capsule's metal skin and had carried them down to the launch pad. The electromagnetic force now attracting the positively charged capsule to the electrons on the ground would be so overwhelming that, at blast-off, the 7 500 000 pound thrust of the Saturn's fiery engines could not budge the spacecraft. The imp, to the bewilderment of the astronauts, would have matched the gravitational force of the whole earth with only a millionth of a gram of electrons.

Within the nucleus of the atom there is a force even stronger than electromagnetism. Scientists have known of this force for just over 30 years, and, today,

the search for an understanding of it is the greatest challenge in physics.

At Serpukhov, Russia, on the other side of the earth from the Saturn's base on Merritt Island, Florida, is the world's largest proton accelerator. Its proton beam acts like the first stage in a multi-stage rocket. But each proton in the beam is boosted to 50 million times the energy it would take to lift it to the moon. It has 76 000 million electronvolts (76 000 MeV) of kinetic energy. Remembering the Saturn's energy needs, it is obvious that physicists studying this stronger force, needing so much more energy, must settle for an extremely small payload. When a small bunch of protons strikes a metal target, the collision produces a multitude of tiny new particles called pions, kaons, and antiprotons. These are separated and collected in secondary beams, which are sent to destinations located deep within the nucleus of the atom.

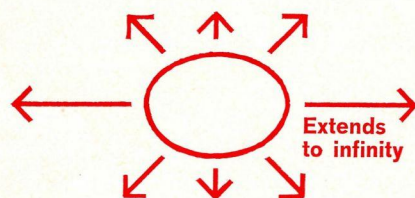
Even as man explores the moon, so will particles in those secondary beams explore a new world — the world of the strong nuclear force. Physicists call it the strong interaction. It binds together neutrons and protons in atomic nuclei. Its pull, particle for particle, is more than a hundred times stronger than electromagnetism, and a hundred followed by 35 zeros times stronger than gravity.

These forces — gravitation, electromagnetism, and the strong nuclear force (plus a little-understood weak nuclear force) — cause all of the variety, change, and beauty in the universe. Without them, objects would never be aware of one another. They would never attract or repel, and they would not collide, but would effortlessly pass through each other. How do forces, which somehow act through what seems to be empty space, account for this? One of the great theoretical achievements in physics tells us the answer, and allows us to see how the strong nuclear force — the strongest force — behaves.

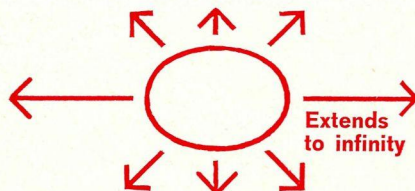
When electrons violently collide, as they do in the sun or in the hot filament of a light bulb, small bundles of kinetic energy are knocked free. The electrons slow down, due to dispersion of some

Nature's Quartet of Forces

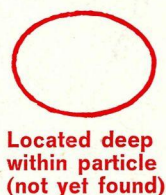
Gravitational force



Electromagnetic force



Weak nuclear force



Strong nuclear force



We can detect a proton only through its forces. It is the sum of four effects. The gravitation force, surrounding all matter in all directions to infinity, controls the stars and galaxies. The much stronger electromagnetic force cancels out at long range, since there are equal numbers of positive and negative charges in the universe. It controls the world of atoms and molecules. The weak nuclear force is known to exist, but its carrier has not yet been detected. The strongest force — the strong nuclear force — controls most effects in the compacted nuclear and sub-nuclear world.

photon of green light, 2×10^{-6} MeV of energy, can be observed only if it exists longer than a million-billionth (10^{-15}) of a second of time. When this photon exists for a shorter time, it cannot be detected.

No photon having measurable energy can be emitted by a static charge on my shirt, but unobservable photons can freely emerge from it at the speed of light and act on a hair. Thus, a stream of 'virtual' photons — so called to distinguish them from the 'physical' photons that we can observe — carries the charges' attraction or repulsion. The less energy a virtual photon has, the longer the time it can act. Thus the farther apart two charges are, the longer the virtual photons take to leap between them, the smaller the energy the photons can possess, and the weaker the force they transmit. The electromagnetic force has an infinite range; infinitely weak virtual photons reach out from each charge to the very horizon of the universe.

This also holds for the gravitational force. Its action is transmitted, also at the speed of light, by particles of energy called gravitons. Though virtual when simply binding the earth to its orbit around the sun, they are, according to theory, emitted physically whenever matter is accelerated. Gravitons must be exceedingly feeble. They have never been observed.

The principle of uncertainty neatly explains the repulsions and attractions between charged particles and the gravitational attraction between all masses. But when the neutron was discovered in 1932, it soon became clear that still another force must bind them to other neutrons and protons in the nucleus. The neutron carries no electric charge, and gravity is far too weak. In 1935, Japanese physicist Hideki Yukawa suggested the new force, based upon the observation that its range is extremely short. Indeed, the pull of the nuclear force comes to an abrupt end at a distance of only 1 *fermi* (a 10-trillionth of a centimeter) from the centre of both neutrons and protons — the two varieties of the *nucleon* (the heavy particle that makes up all atomic nuclei).

Recalling that virtual photons carry electrical forces, Yukawa conjectured that the nuclear force carrier should be a

massive particle. He first assumed that the new force could not spread faster than light, which was not proved experimentally until 1967 by Seymour Lindenbaum at Brookhaven National Laboratory. A photon moves 1 fermi in 10-trillionths of a trillionth (10^{-23}) of a second. Yukawa then used the uncertainty principle to calculate the minimum energy of a virtual particle that can act only this very short amount of time. He found it to be about 100 MeV, roughly one-ninth of the energy — and thus one-ninth of the mass — of a nucleon. This hypothetical force-carrying particle was called a meson.

Scientists could hope to check Yukawa's theory by producing physical, rather than virtual, mesons in violent collisions between nucleons, just as physical photons emerge from collisions of electrons. With their sizable mass, the new mesons should, in fact, be easier to observe. Further, when scientists had bombarded nuclei with neutrons, they found the force that scattered the neutrons had turned some of them into protons, leaving the corresponding nuclei with one less positive charge. Yukawa's force-carrying meson, it seemed, could carry an electric charge as well. A charged meson would expose a photographic emulsion, leaving a characteristic track, or it would leave a trail of droplets behind it as it passed through a cloud chamber. Physicists hurried to study cosmic ray collisions, since protons arriving from outer space would have enough kinetic energy to materialize mesons.

It took 14 years, though, to confirm Yukawa's prediction. First, a particle was discovered that had very nearly the predicted mass, 106 MeV. This particle, called a mu-meson, or 'muon', was thought to be Yukawa's particle for a number of years. But in 1949, Soicho Sakata and Tokuzo Inoue in Japan and Hans Bethe at Cornell University and Robert Marshak at the University of Rochester explained that the muon simply did not have anything to do with the strong force. It was not really a meson. Shortly afterwards, the right particle, the pi-meson, was found. This 'pion' had a mass of 140 MeV, somewhat heavier than Yukawa's prediction. Further, the pion materialized in three states — positively charged,

of their kinetic energy. These energy bundles, called photons, carry the electromagnetic force that moves electrons in your eye — and you can see.

Photons, then, should also carry the force that exists between two charged particles even when neither is moving. Although the static charge on a too-easy-to-charge nylon shirt often is a nuisance, it is scientifically illuminating. For the charge is not moving and can have no kinetic energy, yet it does emit photons. I know of them because they make the hair on my arm stand up. I cannot see these photons, however, even when I am using the finest laboratory instruments.

A powerful principle of physics, the principle of uncertainty, explains why we can observe some photons as lumps of energy but not detect the energy of other photons at all. A photon is the smallest amount of energy that we can measure. We must wait for all its energy to pass by us or see none of it. A definite amount of time, then, depending on the energy of the photon, is needed to detect it. The principle says, for example, that a single

When a high-speed pion strikes a proton, many new particles emerge. Since the K^+ meson, for instance, physically exists longer than its expected life of 10^{-23} second, it must possess a new property, called strangeness, that prevents its strong-force decay into two nonstrange pions. The weak interaction permits the decay, but takes 100 trillion times as long.

negatively charged, and neutral. Three states were necessary to explain why the strong forces between two protons, between two neutrons, and between a neutron and a proton are equal. The light (in weight) particles, called leptons (electrons, muons, neutrinos, and photons) do not 'feel' the pion's strong force. The pion and all heavier particles, which sense its strong force and interact through it, have been named hadrons.

The pion story did not develop without inflicting a few wounds. It is said that Baron Ernest C. G. Stueckelberg Breidenbach, a Swiss physicist, had had the same idea as Yukawa in 1935. He checked it, however, with the renowned Austrian physicist Wolfgang Pauli, who ridiculed it. Pauli apparently tended to be too critical of ideas that were not his own. In any case, Stueckelberg did not publish his idea — and thus did not share the Nobel prize in physics that was awarded to Yukawa in 1949.

Another sequel relates to the muon-pion error. Because of World War II and the lack of scientific communications that followed it, the West had not noticed the Sakata-Inoue paper, and singled out Bethe and Marshak as the scientists who pointed out the mistaken identity. This created bitterness in Japan where it mixed with pro-Communist leanings and resentment over the wartime defeat. The bitterness exploded at a conference held in 1965 at Kyoto, Japan, to commemorate the 30th anniversary of Yukawa's theory. Mitsuo Taketani, one of the most respected of Japanese physicists, nursing personal and political grudges against the United States

and its scientists, came out openly with an accusation of plagiarism. This was countered by Marshak in an intelligent and touching answer. The entire exchange was published in the conference proceedings. Hopefully, this freeing of inner tensions in the scientific body will have cleared the atmosphere.

One might have thought that with the discovery of the pion, the strong force had yielded its secret. But the uncertainty principle tells us that other mesons having higher masses may lurk unobserved deep within the nucleon. The pion turned out to be just a beginning, in keeping with a 'law' of nature. Each time a major advance is made and a mystery solved, we are quickly confronted by a new mystery. Thus, shortly after the discovery of the three pions seemed to completely explain the strong nuclear force, scientists were shocked to discover four heavier mesons. These K-mesons, or kaons, at 500 MeV, were also produced by cosmic rays.

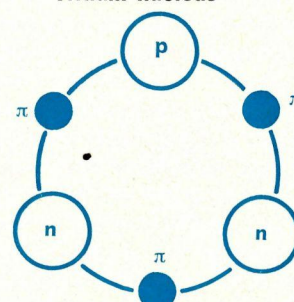
At about the same time, other new particles, similar to protons and neutrons, were discovered in cosmic ray tracks. Called baryons, they were heavier than the nucleon, and decayed into nucleons and pions, or nucleons and leptons. Strong-force decays always occur in roughly the lifetime of virtual pions, about 10^{-23} second. Kaons carried the strong force just like pions, gluing nucleons to the new baryons but not to nucleons. But these new particles all lived 10^{-10} second, more than a trillion times longer than the strong force would take to decay them.

This was a real puzzle. Why were kaons, rather than pions, virtually emitted by the

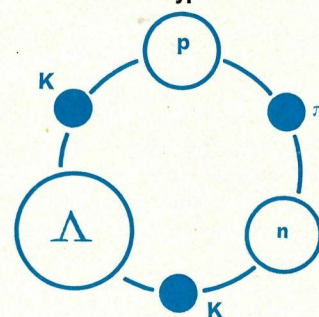
Strange K-mesons can bond strange baryons in ordinary nuclei to make hypernuclear atoms. In tritium, scientists have replaced a neutron with a lambda particle.

Strange Atoms

Tritium nucleus



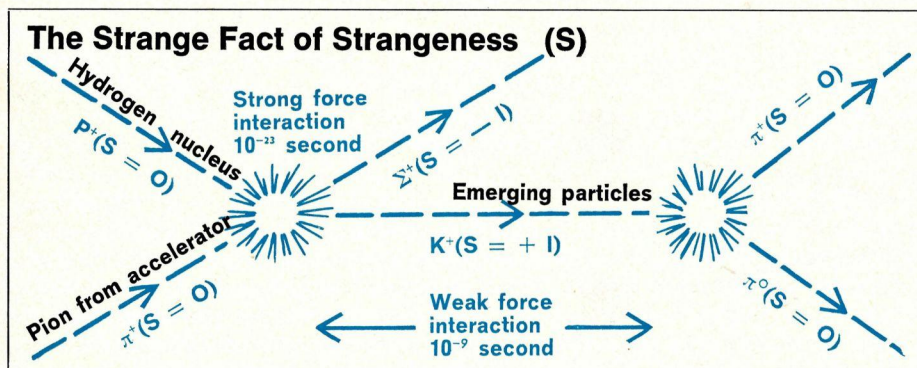
Tritium hypernucleus



new baryons? And why do they live so long? The behaviour of these particles, matter that seemed to have no reason to exist, was explained in 1953 by Murray Gell-Mann, then at the University of Chicago, and, independently, by Kazuhiko Nishijima in Japan.

The new particles must have a new characteristic that is not affected by the strong force. Gell-Mann called it strangeness. The new baryons, he said, each had one unit of strangeness, and were thus unable to virtually emit, or decay into, familiar nonstrange particles in 10^{-23} second. The weak nuclear force apparently allowed strangeness to change by one unit at a time, permitting these strange particles to decay. Its weak accelerations slow the decay rate, however, and the particles live 10^{-10} second, long enough to leave tracks in film or in a cloud chamber.

Strangeness had just managed to explain the role of kaons when experiments carried out by Robert Hofstadter at Stan-



The single unit of spin of the rho-meson, left, is conserved, forcing the two spin 0 pions into which it decays, right, to spin around each other. The detection of orbiting pions first indicated the existence of the rho.

ford University and Robert Wilson at Cornell University provided the next mystery. Yukawa had said that a nucleon should be surrounded by a cloud of virtual pions out to a distance of 1 fermi. Hofstadter and Wilson hoped to observe the cloud by seeing nucleons in atomic nuclei deflect high-energy electrons. Although electrons cannot sense the strong force carried by a negatively charged pion that is virtually emitted by a neutron, they should sense the virtual photons from the pion's electrical charge.

The electron probes did find a cloud, but one that Yukawa's theory could not wholly explain. Yoichiro Nambu, a Japanese physicist working at the University of Chicago and one of the deepest thinkers in particle theory, showed in 1957 that virtual pions could be decay products of yet another virtual meson having entirely different features. This parent meson, called the rho, would have about five times a pion's mass and would decay into two pions deep within the nucleon by the strong interaction. Nambu showed that if the rho was spinning, the two pions, which cannot spin themselves, would have to come out orbiting around each other. Their orbital motion would solve the mystery of the Hofstadter-Wilson cloud.

The spin of the rho tells us something more. A particle's rotation around its axis — spin — can have only specific values. The electron, nucleon, and certain nucleon-like particles are considered to have spins of $\frac{1}{2}$ units. Some heavier nucleonlike particles have spin $\frac{3}{2}$ or spin $\frac{5}{2}$. Force-carrying mesons have a different kind of spin 0, 1, 2, 3. Which spin they have determines the nature of the force they carry. For instance, the force between

identical particles is always attractive if the spin of the exchanged meson is even. The pion has spin 0. The best example of a pionlike force is simple Newtonian gravitation. It does not carry any twisting force; two masses are simply pulled closer together along a straight line between them. Albert Einstein, in his 1916 theory of the gravitational force, better known under the mystifying name of the general theory of relativity, showed, however, that gravity is really carried by a spin 2 particle, the graviton. Attraction is only one aspect of gravity. The graviton's spin creates other effects: centrifugal force, formerly explained by inertial mass, now known to be the same as gravitational mass, and the coriolis force that holds a bicycle upright when its wheels are spinning.

Electromagnetism is transmitted by a spin 1 meson, the photon. This force, carried by an odd-spin meson, is repulsive between identical particles. The whole of magnetism — the twisting force around a moving electron that causes an electric motor to turn — is due entirely to the photon's spin.

The spin 1 of the new rho-meson would imply that it, too, exerts a twisting force similar to magnetism. And the force that it carries between similar hadrons would be repulsive, as in the case of electric forces. This would explain why neighbouring nucleons in a nucleus, pulled toward each other by virtual pions, do not fall into each other. Their central cores of virtual rhos prevent it. Nucleons and their opposite equivalents, antinucleons, however, are attracted together by the pions, and, being opposites, are attracted by the rhos as well. They annihilate themselves.

In 1961, Nambu's theory was confirmed when researchers using particle accelerators found indirect but certain evidence of a physical rho meson. Several other spin 1 mesons were similarly detected.

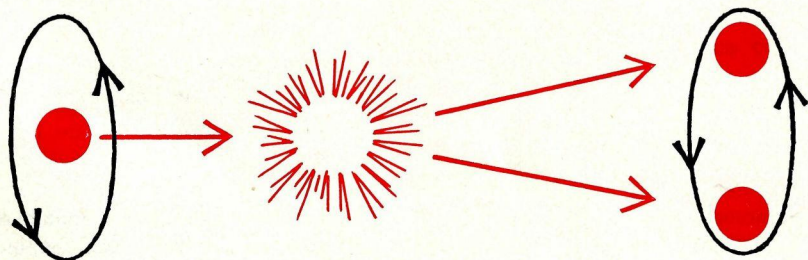
Attempts to measure the strength of the strong force still deeper in the nucleon turned, during the 1960s, to the high energy domain — the region where more massive virtual baryons and mesons should be materialized by cosmic rays and, perhaps, by beams from powerful new accelerators. Mesons having two units of spin were discovered between 1962 and 1964. The strong force, about $\frac{1}{10}$ fermi from the centre of a nucleon, is dominated by these heavy spin 2 mesons, even stronger in their attractive force than the pion.

I sometimes wonder at the fantastic promise of the strong force. The whole of present technology — chemical, electrical, and mechanical engineering — is based upon only two relatively weak forces, electromagnetism and gravitation. Now we see that the strong interaction has, at various ranges, all these effects and more. We shall further see that these forces all come in eights — eight simple attractive potentials, eight complex forces resembling electromagnetism, eight times a gravitation-inertiallike force. What richness when someday engineers will be able to exploit the regions under one fermi. Can this prospect be more remote than Jules Verne's vision of space travel a century ago?

The high-energy studies have shown, as well, that as the energy goes up, the chance of two nucleons scattering each other steadily goes down. Will it, at infinite energies, take a limiting value, perhaps corresponding to the geometrical 'size' of the nucleons themselves? Or will the chance of collision vanish altogether and the particles become completely transparent to each other?

The most recent studies show that at the very highest energies, the strong force is dominated by a meson named for Isaak Ya Pomeranchuk, a Russian physicist who died in 1966. The nature of this 'pom-

Decay of the Spinning Rho



eranchukon' is a mystery. It could be a spin 2 meson, the lightest among them, called the f^0 , at 1250 MeV. It could, however, be a different effect, perhaps the attraction due to the virtual emission of mesonlike proton-antiproton pairs, or other particle-antiparticle pairs emitted and reabsorbed at distances smaller than $1/10$ fermi.

Whether the pomeranchukon is this special object, or the f^0 , will have important implications for future space travel. According to relativity theory, as a spaceship nears the speed of light, the astronauts' bodily processes imperceptibly slow down. They could make hundred-year trips to stars a hundred light-years away in what to them would be just a few years. At these speeds, however, the ship would constantly encounter hydrogen atoms floating sparsely in interstellar space. If the pomeranchukon is the special object, two protons moving toward each other would always have a chance to collide, even at the highest energies. Hydrogen in space would hit the ship extremely hard, like cosmic rays, and this intense radiation could be one of the strongest reasons against the hope of travelling to the stars.

If, instead, the pomeranchukon is the f^0 meson, the chances of protons colliding would diminish with every increase in their energy. At infinite energy, the strong force would vanish, and the protons would never collide. A spaceship and its occupants could cruise extremely close to the speed of light and be unaware of the hydrogen gas passing harmlessly through them. The question of which is the correct view is one of many that will be answered by two giant accelerators to be completed in the 1970s, one by the U.S. Atomic Energy Commission at Batavia, Ill., and the other by the European Organization for Nuclear Research (CERN) in Europe.

While measurements of the strong force gradually advance, another approach has brought a much needed order into our picture of the nucleon. The situation is similar to that of natural history. Charles Darwin's theory of evolution emerged only when the animal kingdom had been sufficiently classified. Noting similarities and

regularities, Darwin could trace descents. Sir Isaac Newton's theory of gravitational and inertial forces could come only after regularities and similarities in the motion of planets and falling objects had been discovered by Johannes Kepler and Galileo Galilei.

Early in 1961, Murray Gell-Mann and I independently suggested a scheme that classified strongly interacting particles into family groups. Previous attempts had failed. All the hadrons simply did not fit. One scheme had come close to success, however. It was based upon an idea of Sakata's, in 1956, that the proton, the neutron, and a strange particle, the lambda baryon, plus their antiparticles, were the basic building blocks of all particles, and thus of all matter. In 1960, Yoshio Ohnuki in Japan and Walter Thirring in Austria uncovered a 19th century mathematical technique known as SU (3) — for Simple Unitary group of transformations in 3 complex dimensions. This SU (3) is an especially good tool for manipulating groups of three basic objects. They found that by combining Sakata's charged particle, neutral particle, and strange particle in various ways, all the known properties of hadrons could be explained.

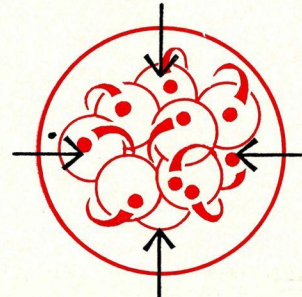
The scheme predicted that mesons having the same spin should arrange in groups of eight. Thus, the seven known spin 0 mesons — the three pions and the four strange kaons — should have an eighth companion. At the University of London, in 1961, Abdus Salam and John C. Ward extended Ohnuki's eightfold prediction to the spin 1 mesons as well, and suggested that the rho, if found, should likewise have seven spin 1 companions.

Baryons, however, not having the whole-number spins of the mesons, fell into 3-, 6-, and 15-member groups. Because Sakata had assumed that certain baryons, the neutral xi, for instance, were made by adding together three spin $1/2$ baryons, they were predicted to have spin $3/2$, and a more complicated structure than the nucleon.

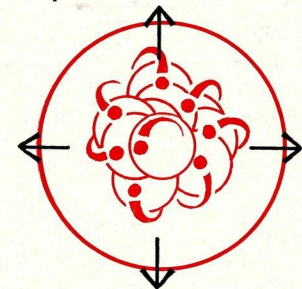
At about the same time, and without knowing of Sakata's theory, I was looking into the same problem. I hit upon the adequacy of the eightfold scheme as the simplest mathematical structure that could classify the strong interactions. The same

The Pulsing Nucleus

Spin 0 attraction



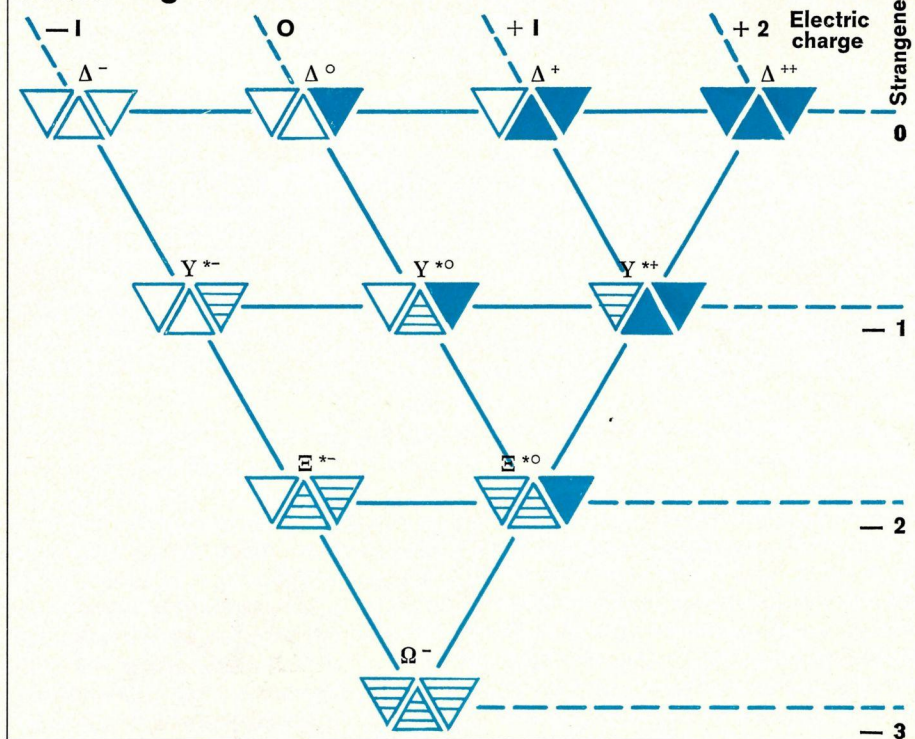
Spin 1 repulsion



Forces carried by pions and rho-mesons alternately attract and repel nucleons in an atomic nucleus. Spin 0 pions keep the nucleus from flying apart; spin 1 rhos keep it from collapsing.

The discovery of the spin 2 f^0 meson hints that if nucleons could be squeezed beyond the resistance of the rho forces, they would attract each other with enormous force. This would not only release staggering amounts of usable energy, but should also produce a new kind of matter. The rho's repulsion, however, does not weaken fast enough to allow this attraction except when two nucleons glance off each other at high speed.

Combining Quarks



Three kinds of objects, shown as coloured triangles, can be arranged into ten possible groups of three. In *The Eightfold Way*, each combination of three fictitious objects, called quarks, makes a different baryon.

idea occurred to Gell-Mann, at the California Institute of Technology (Caltech). Neither of us had any notion, however, of using known particles as fundamental 'bricks', as in the Sakata model. We both felt free to arbitrarily arrange the existing particles in various patterns, without concern for their building blocks, and see which pattern best fit the observations.

We thus found, unlike Ohnuki and Thirring, that, of all mathematically possible structures, the arrangement of the eight then-known baryons into one family best explained the facts. Mathematically, this meant that we had used three fictitious objects as the building blocks, and made all the baryons, including the nucleon, from various combinations of the three types. In our 'synthesis', then, the xi would be no more complicated than the nucleon and would have the same $\frac{1}{2}$ spin. Our theory also predicted the existence of eight spin 0 and eight spin 1 mesons. I published this, and so did Gell-Mann, early in 1961.

Within just a few months, the eighth spin 0 meson was discovered. The eight spin 1 mesons were also found in 1961. In 1964, the spin 2 mesons were found, and arranged themselves neatly into the same kind of octet.

Up to that point, it was not clear which theory was correct, the Sakata model — the more popular one — or 'The Eightfold Way', as Gell-Mann had named ours. Eight-member meson families had been predicted by both models. The spin of the xi was found to be $\frac{1}{2}$ in 1963 and seemed to indicate we were right, but the

relative simplicity of Sakata's scheme still attracted many physicists.

One clear-cut difference could be drawn. If our scheme was right, baryons having spins of $\frac{3}{2}$ should exist as a 10-member family. Four had been discovered by Enrico Fermi in 1950. Another three, each with one unit of negative strangeness, were reported in 1961. And, at the 1962 CERN conference, held in Geneva, Switzerland, a pair with two units each of negative strangeness was reported. Their spins were not known. If these nine really made up a family, the 10th member should have three units of negative strangeness. Moreover, all nine decayed by the strong interaction in 10^{-23} second, and could be identified only by complex analyses of the decay products. Their 10th companion, though, could decay only by the weak nuclear force, as its mass would be smaller than any decay products having the same strangeness. It should thus live about 10^{-10} second and leave a track in a bubble chamber.

All the properties of the missing particle could be predicted from our theory. Gell-Mann went to the blackboard during the CERN conference and explained exactly what the experimenters should be looking for. I had made a similar suggestion the day before in a letter to Gerson Goldhaber and his late wife and collaborator, Sulamith Goldhaber. An experiment with negative results that they had reported just two days earlier had provided the last needed clues, and I was trying to convince them to look for the missing tenth piece of the puzzle.

In February, 1964, Nicholas Samios and 32 collaborators at Brookhaven National Laboratory found it — the first omega-

minus particle. Since then, only 20 or so omega-minus particles have been observed. They have the right mass (about 1,680 MeV), charge, strangeness, and also, I hope, the right spin, since this has not yet been measured.

Thus, The Eightfold Way worked. Since then, many other predictions of The Eightfold Way have come true, so that the theory has been adopted by most physicists. From a particle's position in its family pattern, we can predict the relative strengths of the force between it and the various hadrons. The scheme even goes beyond the strong force, explaining their weak force and electromagnetic interactions, too. But we still do not know why The Eightfold Way should hold. Today's Newton has not yet appeared.

In 1964, Gell-Mann and Georg Zweig at Caltech suggested checking whether the three fictitious particles we had used as elementary really exist as virtual or physical particles. Gell-Mann called them quarks. In four years of searching, however, they have not been found, and the chance that they exist seems to be dwindling.

My own feeling is that the final theory of matter and its strongest forces will not have the naive simplicity of three truly elementary particles obeying the rules of The Eightfold Way. Nature will be more clever. Indeed, if quarks are ever found, I am sure that we shall be faced with an even deeper mystery. In 1968, a colleague who has lived through the entire history of elementary particle physics told me that the first two high energy accelerators — the Bevatron at Berkeley, Calif., and the Cosmotron at Brookhaven, N.Y. — both broke down shortly after they began operating in 1954. Six months went by before the experiments could be continued. The Creator probably had given himself time to put some complexity into this smallest of worlds that men were beginning to explore. Let us not underestimate the sophistication He will be using next.

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