

At the accuracy now expected for the muon, the experimental value is confirming the validity of the theory of quantum electrodynamics down to distances of 10^{-15} cm and energies equivalent to over 20 GeV. It is confirming the calculations which the theorists have extended to include higher order terms (many photon exchanges as discussed above) and is beginning to reach levels where the existence of the strong interaction is expected to influence the observed values. It is also confirming the view of the muon as simply a heavy electron. One comment aroused by the precision of the measurements is that 'the g-2 value acts as a great restraint on the fantasy of theorists'.

One cloud did appear on the QED horizon when the Lamb shift measurements moved out of line with theory but this was dispelled about 1970 when S. Brodsky spotted an error in the calculations. Since then, theory and experiment have lined up with a perfection which would have staggered the physicist of 1954.

So, is everything rosy in our understanding of the electromagnetic force? No, because there are two long-standing mysteries and a new worry which has raised its head only in recent months.

The first mystery concerns the existence of the muon. To quote I. Rabi 'Consider the muon. Whoever ordered that?'. It is believed that the mass of a particle is a consequence of the interactions it undergoes. If so, how can two particles be so identical as the electron and the muon which seemingly differ only in their mass? Where is the force felt by the muon and not by the electron? Are there other heavier particles, so far unidentified, resulting from whatever it is that turns the muon on?

The new worry comes from the high energy electron-positron storage ring results reported in the February

issue. If the production of hadrons in electron-positron interactions continues constant as the measurements are taken to ever higher energies, then the strong interaction influence on electromagnetic interactions would no longer be calculable. The present closed nature of the QED calculations would be spoiled and new, at present unknown, factors would have to be fed into the sums.

The second mystery is in the very roots of the theory. Why do we have to plug in the observed mass and charge of the electron or muon (the process of renormalizing the theory) in order that the calculations work with such perfection? The theory, left to itself, gives infinite values for both of these quantities. It would obviously be philosophically more satisfying if the observed mass and charge emerged naturally from the theory itself.

Perhaps the electron is a black hole! One can plausibly argue that its Schwarzschild radius of about 10^{-55} cm would give it enough size to get rid of the infinities in quantum electrodynamics and give the correct electron mass. So perhaps gravitation is deeply involved with the electric properties of matter but so far no firm framework has been found for these ideas.

Altogether, from 1954 to 1974 our understanding of the electromagnetic force has remained in surprisingly good health. It has been shown that it can predict, with accuracy, the effect of the electromagnetic force over a vast range of distances from 10^{-15} to 10^{10} cm.

The strong force

Compared with the order which has reigned in the observations of particle behaviour under the influence of the electromagnetic force, the observations of behaviour under the strong force have opened up a completely new world. *

In 1954, the interpretation of the strong force was still dominated by the insights of Yukawa many years previously in 1935. He interpreted the interaction between two hadrons in terms of the exchange of mesons (later called pi mesons or pions). This can be seen as the proton having a virtual pion cloud associated with it, just as the electron has a virtual photon cloud associated with it. There is a considerable difference between the two pictures however.

It is clear, first of all, that the meson cloud produces a much more powerful effect than the photon cloud — the strong force between protons in the nucleus holds them together despite the electromagnetic force due to their positive charges trying to push them apart. Secondly, the range of the force is very short (about 10^{-13} cm) — the protons stick together only if brought within nuclear distances of one another. This second clue led Yukawa to the pion. Using the uncertainty principle, as discussed in the article above, and knowing the time to travel 10^{-13} cm at the speed of light (10^{-23} s), he could calculate the minimum energy which a particle could have to traverse this distance while remaining as a virtual particle. It came out at around 100 MeV. The pion, when first identified in 1947, proved to have a mass of 140 MeV.

The predominant picture in 1954 was therefore of protons and neutrons bound in the nucleus through the intermediary action of pions (positive, negative and neutral charged forms

Perhaps the most famous bubble chamber picture in history — the detection of the omega minus particle predicted by the classification scheme of unitary symmetry. It was taken in the 80 inch chamber at Brookhaven and crowned the efforts to put some order into the plethora of particles, which were found at the high energy accelerators in the late 50s/early 60s, being produced under the influence of the strong force.

accounting for the equal strengths of the interactions proton-proton, neutron-neutron and proton-neutron).

Trouble was already brewing at that time. A heavier meson, the kaon, had been spotted in nuclear emulsion photographs of cosmic rays and heavier baryons (heavier variants of the proton and neutron such as the lambda and sigma) had been seen. But they were initially thought of as rather exotic entities and did not rock the Yukawa boat immediately. They needed something new, however, to explain their behaviour. The kaons were the intermediary of the strong force between the proton and the new baryons (but not between the protons themselves) and a property called 'strangeness' was conjured up for the new particles by M. Gell-Mann and K. Nishijima to explain why this limitation applied.

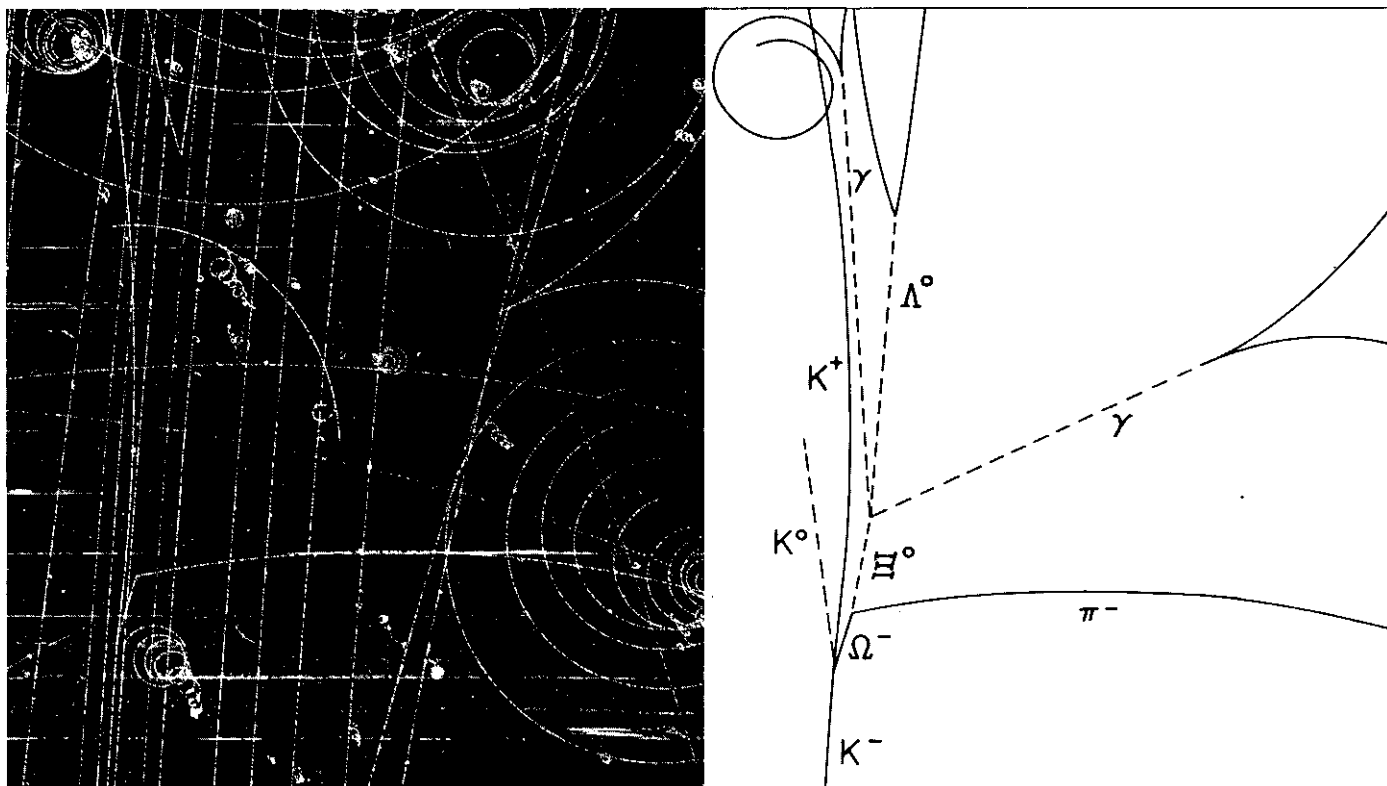
Doubts really began to multiply

when the Hofstadter experiment, mentioned above, indicated that the proton charge radius was smaller than the Compton wavelength of the pion. Y. Nambu analysed this problem theoretically and suggested in 1957 that another virtual meson, a heavier mediator of the strong force, be called into play. Pions could themselves be produced in the decay of the heavier meson, which was called the rho meson. This new particle was detected in 1961.

The floodgates really opened when the large bubble chambers of L. Alvarez came into operation at the Berkeley 6 GeV Bevatron. Through to the early 1960's, a whole host of new mesons and baryons were identified and many of their properties measured. The list has grown to include over 200 distinct particles. High energy physicists became like botanists recording the features of plant after plant as they walked through pastures new.

This was the first big change and a change from which we have still not recovered. The simple picture of Yukawa was obviously inadequate to absorb the behaviour of this multitude of particles, yet, even now, no convincing picture has been put in its place. There has, however, been a lot of tidying up — a lot of elegant work which has demonstrated remarkable relationships within the large family of particles and it must surely be true that some deep reasons exist for the similarities in behaviour that we observe.

The most important advance in classifying the particles came in 1961 from Y. Ne'eman and M. Gell-Mann. They used a mathematical technique from 19th Century group theory, called SU(3) — simple unitary group of transformations in three complex dimensions — which is a technique for studying sets of three basic objects. Applying this to particle pro-



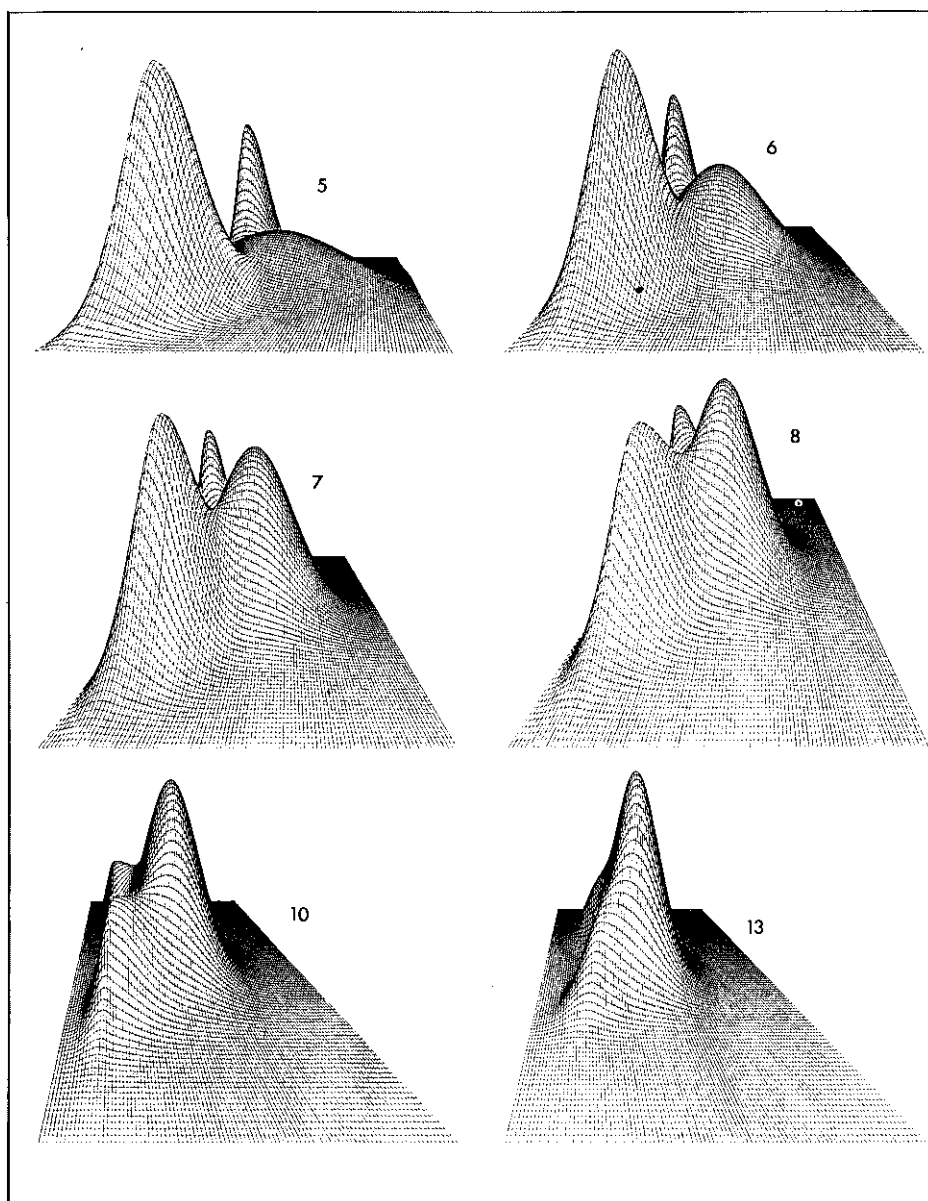
To illustrate the new flood of information coming with the opening up of higher energy ranges at Batavia and the CERN ISR, is this presentation of strong interactions resulting in the emergence of many particles from an experiment at the ISR. Each diagram corresponds to a number of emerging particles (5 to 13). When only five particles emerge, most of the events involve the 'fragmentation' of one or other proton (the two high peaks) and only a few involve the 'central region'. But the higher the number of particles, the more the central region events dominate until, with thirteen emerging particles, they are almost entirely from central region events.

perties, they classified the particles in groups, usually called multiplets. What Ne'eman and Gell-Mann were doing mathematically was to treat the known particles as if in reality they were built up of three more basic 'building blocks'.

The scheme predicted how the particles should group together. For example, it said that all mesons of the same spin should exist in groups of eight. An eighth companion for the three zero spin pions plus the four zero spin kaons was found in 1961; eight spin one mesons like the rho were also found that year; eight spin two mesons were found by 1964. The most spectacular prediction was of the existence of the particle now known as the omega minus. Playing with their three mathematical blocks, they grouped the baryons of spin $3/2$ in a group of ten and by 1961 nine of these had been identified. During the CERN conference of 1962, Gell-Mann wrote on the blackboard the mass (1680 MeV), charge (minus one) and strangeness (minus three) of the then missing tenth member. At the beginning of 1964, the omega minus, with precisely these properties was seen for the first time at Brookhaven.

This really rubbed home the validity of the classification scheme and (following work by G. Zweig and Gell-Mann) opened the hunt for physical objects, usually referred to as quarks, inside the hadrons which would correspond to the mathematical objects of $SU(3)$. There is still no sign of an individual quark but $SU(3)$ has worked magnificently in classifying the known hadrons and its implication of something deeper within the hadrons looks ever more valid as more and more experimental data is accumulated.

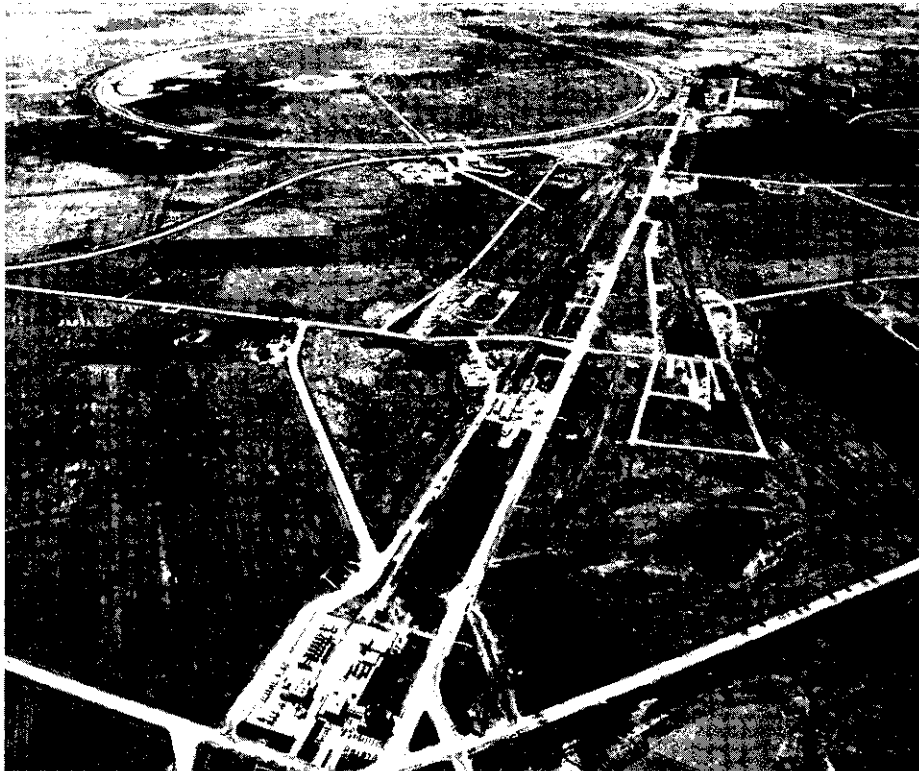
Had this sketch of the role of the strong interaction in the behaviour of particles been written a few years



ago, we could stop here with a tantalising theoretical indication of another layer of the onion of matter, but very little experimental indication except for the success of the classification scheme. Many frustrating years followed the advent of $SU(3)$. Experimental data poured in. Theoretical schemes showed up further remarkable relationships — the Regge trajectories and their exchange mechanism, the duality concept, the

multiperipheral model — but no deeper insight really emerged.

They were all useful concepts for categorizing what was being seen. They had considerable predictive power — they could predict new particles of higher spin; they gave the energy dependence of interaction cross-sections; they could bring out the rate of increase of particle production as the energy goes higher. But none of them really passed from



The two sources of completely new information on the strong force:

- 1) The 400 GeV accelerator at the Fermi National Accelerator Laboratory, Batavia, is seen in the background in this aerial view. The ejected protons travel to the experimental areas towards the bottom of the picture.
- 2) The CERN Intersecting Storage Rings of which one intersection is pictured here showing the two crossing beam pipes surrounded by detectors.



the stage of being a useful concept for describing what we saw into the stage of giving a true understanding of what we saw. Also, when pushed to describe detailed features of particle interactions due to the strong force, the concepts fell over.

In the 1970s two new features have been fed into the strong force picture. The first is the result of access to higher energies at the CERN Intersecting Storage Rings and at the 400 GeV synchrotron of the Fermi National Accelerator Laboratory in the USA. Prior to their operation, particle behaviour had been studied almost entirely in terms of 'two-body' interactions — when a hadron meets a hadron giving two other particles emerging. To tackle the situation when more than two particles emerged looked a daunting task — after all we could not even make real sense of the seemingly more simple 'two-body' case.

The higher energy collisions make it more difficult to leave aside the 'multi-body' events because particles pour out in profusion from the higher energy strong interactions. The big surprise has been that analysing these multibody events at very high energy is very much simpler than could be anticipated from what was seen before. Particles may pour out in profusion but the underlying phenomena can be distinguished with greater ease.

Let us look at the information coming from the proton-proton collisions in the ISR. Leaving aside the purely elastic events, where the protons effectively bounce off one another, we can see two types of interaction. In one type, one proton remains itself but the other one is severely disturbed and sheds pions. This type has collected the name 'diffraction dissociation' collisions. The other type (often called 'pionization' collisions) sees both protons disturbed and the production of pions in large numbers. Even with the large number of par-

tides there seems to be something fairly simple going on because strong correlations are seen (for example, if a positive pion of a certain energy flies off, we are likely to find a negative pion around with very similar energy).

This surprising simplicity has swung our thinking about the strong force onto new paths. The pouring out of pions in pionization collisions while protons emerge perhaps excited but essentially intact, is likely to be a profound clue to the nature of the strong force.

Before saying more about this, let us return to the second piece of information of the 1970s. The success of the SU(3) scheme seems to be telling us that a baryon, e.g. a proton, contains three 'building blocks' or 'quarks', each carrying a fraction of the proton electron charge ($1/3$, $2/3$ and $-1/3$).

The 22 GeV linear accelerator at SLAC (Stanford) has looked at the proton with electron beams to see where the electromagnetic force is effective, i.e., how the electric charge is distributed inside the protons. The result agrees with a picture where it is concentrated on three 'grains' of diameter at least ten times smaller than the proton, the grain charges being again $1/3$, $2/3$, - Vs. It is therefore natural to identify these point-like grains with quarks. The Stanford experiments show in addition that in a high energy proton, about half the energy is carried by the grains, the other half being carried by hadronic matter which is essentially uncharged and is often speculated to be a kind of 'glue' holding the grains together. The neutrino experiments, especially the CERN experiment with the bubble chamber Gargamelle, have looked at the hadron to see where the weak force is effective (the neutrino, being a lepton and carrying no charge, only feels the tiny weak force). Again the three grain picture emerges.

Returning now to our high energy strong interactions at the ISR, in particular the pionization collisions: We see that our protons emerge essentially intact (in other words, still as a bound three-grained object), albeit with about half their original energy, while a clutch of pions are left in their wake. It is as if the grains go through with about their share of the proton energy, while the glue produces the many pions emerging from the collision, each with rather low energy.

When a hadron gets involved with the weak or electromagnetic force, the glue seems quiescent but when it gets involved with the strong force the glue becomes highly activated and results in an outpouring of pions. The glues of two hadrons stick together as the grains rush on. The correlations which are seen in the outpouring, tie up with this sort of picture.

So perhaps we are evolving a new picture of the hadrons and thus of the strong force. But the experimental information is new and will no doubt be augmented considerably in the next few years, so any interpretation at this stage is a first shot at a deeper understanding. There are obvious problems such as our inability to extract the grains themselves. And also there is this very recent information on hadron production in electron-positron annihilation collisions, mentioned when discussing the electromagnetic force above. This fits no picture that we can draw at the moment.

Compared with twenty years ago, the behaviour of particles under the influence of the strong force has proved rich beyond belief. We have seen the force in action in a myriad different ways. Our view of the hadron is completely transformed. But we still cannot claim that we really understand what we are seeing.

The weak force

Experiments with high energy accelerators have revolutionized our knowledge of particle behaviour under the influence of the weak force every bit as much as they have of the strong force. With the weak force it is perhaps less surprising since the probability of weak interactions taking place rises in proportion to the energy and it is only at high energies that we begin to see the force at work in a variety of ways.

Prior to 1954, practically all the information on the weak force came from observations of beta decay — the emission of an electron from a nucleus due to the breakup of a neutron to give a proton, an electron and a neutrino. The mysterious neutrino had been seen for the first time a year previously in a reactor experiment by F. Reines and C.L. Cowan. This cost W. Pauli a case of champagne. When he postulated the existence of the neutrino in 1931 in order to make sense of the energy and spin balance in beta decay, he thought that the likelihood of a particle which only feels the weak interaction ever being observed made a champagne wager a safe financial proposition. Cowan and Reines, however, used the flood of neutrinos from beta decays in a nuclear reactor to spot their interaction with a proton to produce a neutron and an electron.

The theory of how the weak force worked dated back to E. Fermi in 1934. He modelled it on the theory of the electromagnetic interaction — hence come the terms 'charged current' and 'vector force' in analogy to the electric current and electric and magnetic vectors. Since the force seems to be effective only over an extremely short range, he treated the interaction as 'point-like' with no need for an intermediary particle such as we call for in