Nishina Memorial Lecture

ARE WE REALLY MADE OF QUARKS?

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July, 2000

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Nishina Memorial Lecture delivered at
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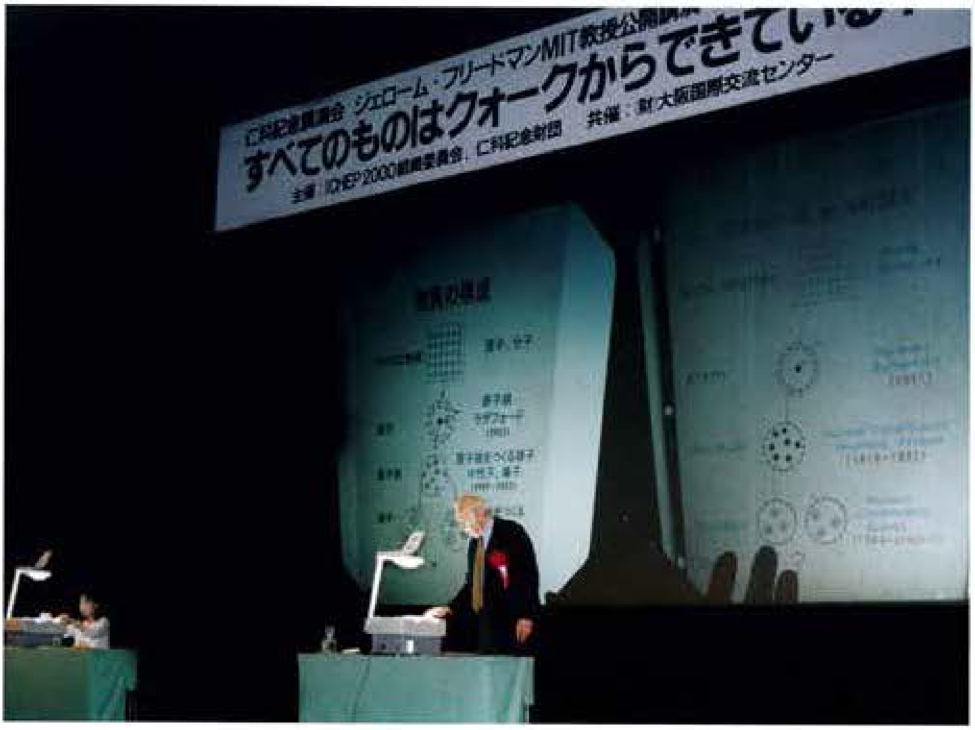
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Are We Really Made of Quarks?

Professor Jerome I. Friedman

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Thank you for your kind introduction. It is a great honor and pleasure to present the Nishina Memorial Lecture to an audience in the city of Osaka, and I want to thank the Nishina Foundation for inviting me. I consider this a very special honor because Professor Nishina was one of the great pioneers of modern physics. As you see, the title of this talk is - Are We Really Made of Quarks? We physicists believe we are. And the question is - Why do we believe this? This is the story I want to tell you today.

If you look at the stable matter in our world and in the stars and planets beyond us, it's made of 3 objects: electrons, UP quarks and DOWN quarks. This is a surprisingly simple picture. But we didn't come to this conclusion very easily. There was enormous controversy about the quark model and its relevance. The quark model violated cherished points of view; and it was not accepted until a great deal of experimental evidence came in., overcoming the arguments of skeptics.

Let me first start by giving an introduction to the hierarchy of the structure of matter. Looking at the top of the view graph we see just ordinary matter, consisting of atoms and molecules. Everything here is made up of such matter, this table, us and everything around us. If we increase the magnification a 100 million times, we see the atom. The atom consists of electrons going around a positively charged small object in the center called the nucleus. That picture was proposed in 1903 by Hantaro Nagaoka, who later became President of Osaka University. In 1911 this model was confirmed by Rutherford in a famous series of experiments using the scattering of alpha particles. If we now increase the magnification another 100,000 times, we see the nucleus , which is composed of neutrons and protons. That picture started unfolding in 1919 and culminated with the discovery of neutrons in 1932 by Chadwick. If we increase the magnification further, we see that the proton and neutron are composed of other particles called quarks. That story started unfolding in 1968 and goes on to the present. That's the story I want to tell you.

What particles existed in 1946? The electron was discovered by J.J. Thompson in 1897; and we have the positron, which is its anti-particle, that was discovered by Anderson in the cosmic rays in 1932.

STRUCTURE of MATTER

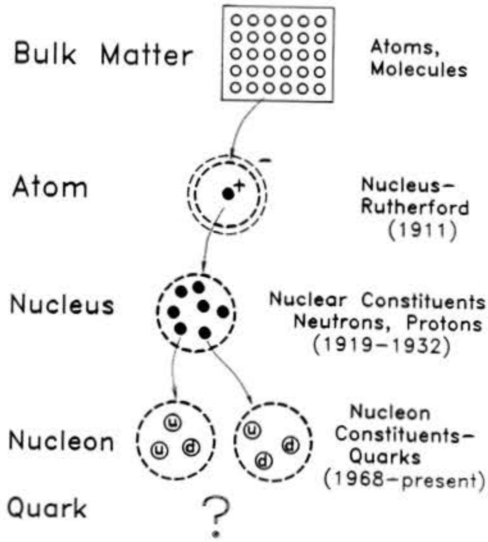

Fig.1

In 1936, another particle was discovered called the muon. This was a great surprise because it has all the properties of an electron except that it is 200 times heavier. Nobody understood what role it played in nature. In fact when it was discovered, the physicist I.I. Rabi asked, "Who ordered that?", and it was not understood for many years. There were the proton, neutron, and the photon, which basically is just a quantum of energy of electromagnetic radiation, such as gamma rays, x-rays, light, and radio waves. There was also the neutrino - it's another interesting particle. In the early experiments on beta decay, that is radioactive decay of unstable nuclei, it was observed that energy was not conserved. Since physicists don't like to give up a cherished conservation principle, it was hypothesized by Pauli in 1931 that particles were being emitted in beta decay which could not be detected. These particles were called neutrinos. It wasn't until 1956 that the neutrino was discovered. The pion was proposed in 1935 by the famous Japanese physicist, Hideki Yukawa. This was an interesting prediction. By looking at the behavior of the nuclear forces, that is the forces between the neutron and proton, the proton and proton, and the neutron and neutron, and by using the observations of how far these forces extend in space, Yukawa predicted the existence of a new particle. He predicted its approximate mass, and physicists started searching for it because the argument was very compelling. Yukawa, who was a Professor at the University of Osaka, was awarded the Nobel Prize in 1949 for this pioneering theoretical work.

In 1947 this particle was discovered, and it was called the π meson. This was the famous photograph in which its discovery was announced. This particle was first seen in nuclear emulsion, which is just a thick photographic plate that you look at with a microscope. Here's the π coming in, and as it's coming in it slows down and then stops. It then decays into a muon which goes on here and then finally stops and decays.

Ref. 2.5: Discovery of the decay $\pi \to \mu\nu$

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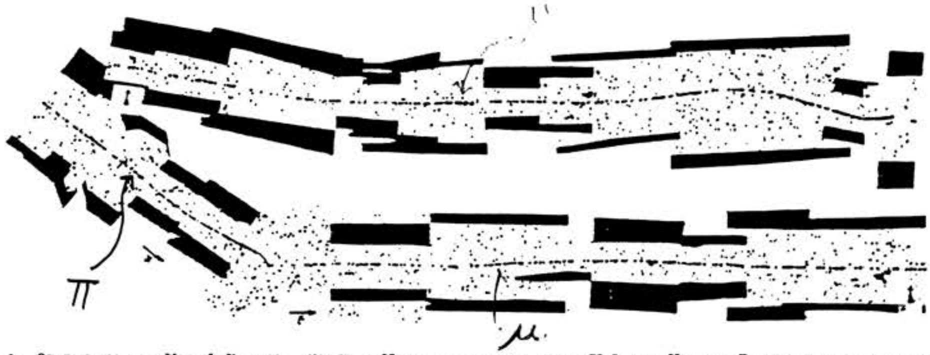


FIG. 1. OBSERVATION BY MRS. I. POWELL. COOKE × 95 ACHROMATIC OBJECTIVE: C2 ILFORD NUCLEAR RESEARCH EMULSION LOADED WITH BORON. THE TRACK OF THE μ-MESON IS GIVEN IN TWO PARTS, THE POINT OF JUNCTION BEING INDICATED BY a AND AN ARROW

Fig.2

This was a great triumph and there was enormous elation in the community. The newly discovered particle had the right mass, which could be determined by various methods. There was a feeling that perhaps there was some understanding of what was going on. But that enthusiasm was very short-lived because what happened after the pion discovery was that great complexity developed very rapidly in this field. This complexity was driven by new technology in the form of new accelerators called synchrotrons and new types of detectors, primarily the bubble chamber. These were important instruments in the story of how quarks were proposed and discovered.

I will say a few words about the bubble chamber. Basically, it's a pot of liquid in a so-called super-heated state. The liquid is just about ready to boil. There is a piston which you raise very rapidly and this decreases the pressure. It's like opening up a bottle of carbonated water. When you open a bottle carbonated water-, you release the pressure and you see bubbling. In the same way, the liquid in the bubble chamber has the tendency to bubble when the piston is raised. Now what happens during that time is that a beam of particles comes in and the particles interact, producing all kinds of particles. Each track seen in the chamber is the result of a charged particle going along, ionizing the atoms in the liquid. And how does this work? The charged particles knock out electrons from the atoms and because these atoms are damaged and emit low energy electrons, they become the centers for bubble formation. So bubbles form along the paths of the particles and just at that point, you strobe a light on, causing the camera here to take a picture. Then you lower the piston which stops the boiling and you're ready to start all over again and take another picture. There is one other element that you should be aware of - that you put the bubble chamber in a magnetic field, because when a charged particle moves in a magnetic field it goes around in a circular orbit and the radius of curvature is equal to the particle's momentum divided by the charge of the particle times the magnitude of the magnetic field. And so if you measure the radius of curvature you can tell what the momentum is. The momentum is just the mass times the velocity and you can therefore determine the energy of the particle. So you can measure everything that is required to resolve some of the issues in the identification of particles.

Here is, for example, a bubble chamber picture. You see here how a low energy proton hits another proton in this bubble chamber and these particles are produced. You can see the track curvature here caused by the magnetic field and you see these are different charges. This is one charge and this is another charge of the opposite sign, as you can see from the opposite signs of the radius of curvature.

And so that's what a low energy interaction looks like. Then you have a high energy interaction which can be seen in the next view graph. You see this very high energy particle coming in and it has this catastrophic collision, producing many, many particles. You see all of these particles being made in this collision.

And here's another picture that I always like to show because it shows two features that are very nice. This is a picture of high energy photons, producing electron-positron pairs. This is actually a confirmation of the fact that you can convert the energy of the photon, which has no rest mass, into the rest masses of the positron and the electron. So this is a verification that $E=mc^2$.

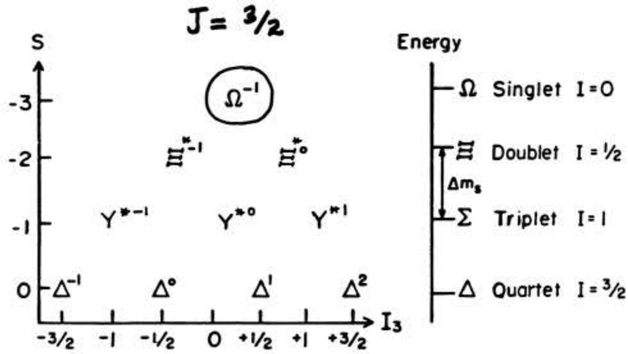
Another thing you see here - the spirals. What are the spirals? Remember I told you that charged particles going through material ionizes atoms in the material. Well when a particle ionizes material, it has to lose energy. Losing energy, it has to spiral in because the radius of curvature is proportional to its momentum which is decreasing with its energy.

As a result of this experimental technique, many new particles were discovered. There was a particle of the month club in those days. By 1966 about 60 different particles were discovered. We called them elementary particles, but the question is - If you have 60 of anything, can they be truly elementary? People started wondering about that.

This was the genesis of the quark model. What happened then was that in 1961 Gell-Mann and Ne'eman independently developed a classification scheme for these many newly discovered particles. It was like the periodic table of the elements except that it was for particles. It was based upon having particles organized into families of the same spin and parity. Don't worry about parity, a quantum mechanics concept we don't have to discuss. Spin is a concept that is somewhat more accessible. Particles have the properties of a spinning top, described in terms of quantum mechanics. Then in 1964 Gell-Mann and Zweig independently proposed quarks as the building blocks of these families.

I will explain these ideas now. Here for example is one of the families for a certain spin - spin 3/2. The thing about this scheme which made it useful was that it was predictive as well as descriptive. If it was just descriptive, it would have been of no use- it would just be numerology. But it was very much like the periodic table of the elements. It was predictive. In the early 60's most of the particles in the spin 3/2 family had been discovered. But the heaviest particle of this family was missing. Physicists who worked on this problem believed that this particle, the so-called omega-minus, had to exist. It was a very unusual particle. In addition to being very heavy, it has unusual quantum numbers, but I don't want to go into this because it's not important for this discussion. As a result of these considerations, everybody in the world who could search for this particle started searching for it. If this particle were not found, this classification scheme would not be viable.

In 1964, after looking through 100,000 bubble chamber pictures, physicists at Brookhaven National Laboratory found one such event. And this is the picture that includes the event. You have to really admire the people who found this because it's hard to see the event in the picture. It was a real tour de force to find it. Because everything could be reconstructed on the basis of energy and momentum conservation, the mass of this particle, the omega minus, was measured. The particle was discovered with just this one event. There was tremendous elation because it meant that the classification scheme had validity, and of course other predictions started coming in too.



Predictive as well as Descriptive

Fig.6

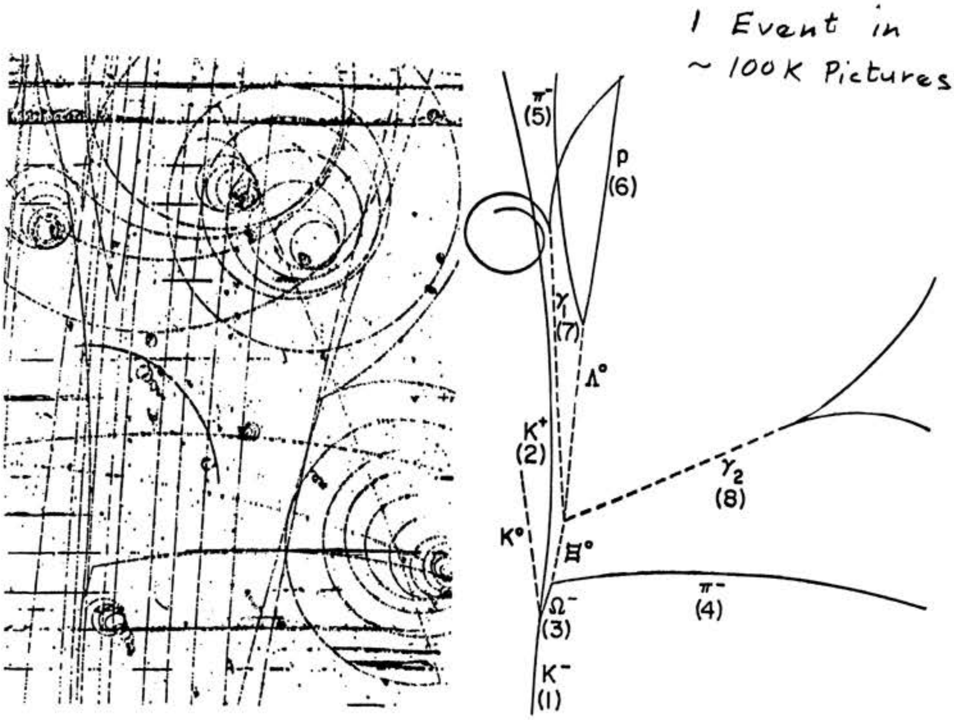


Fig.7

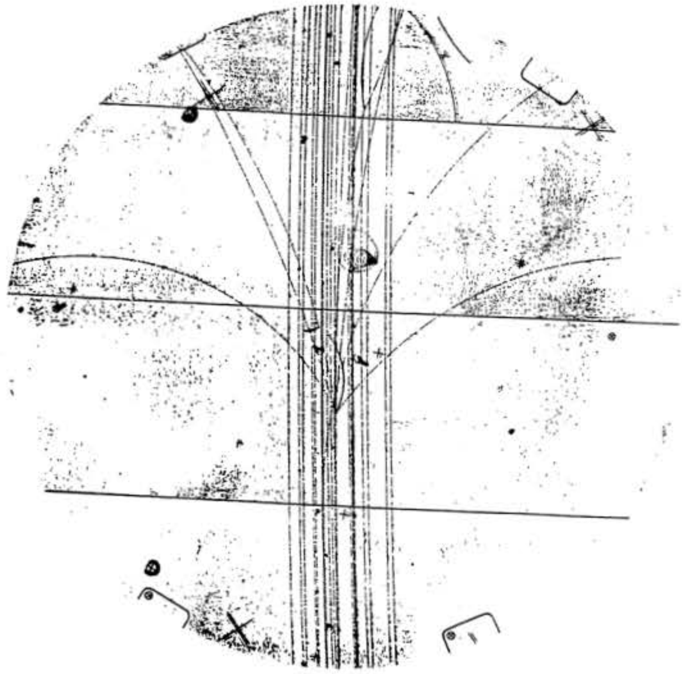


Fig.3

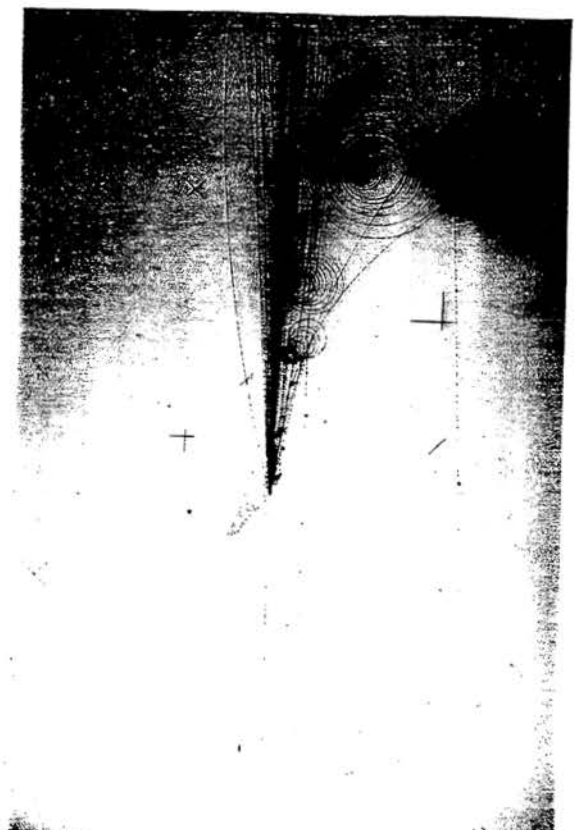
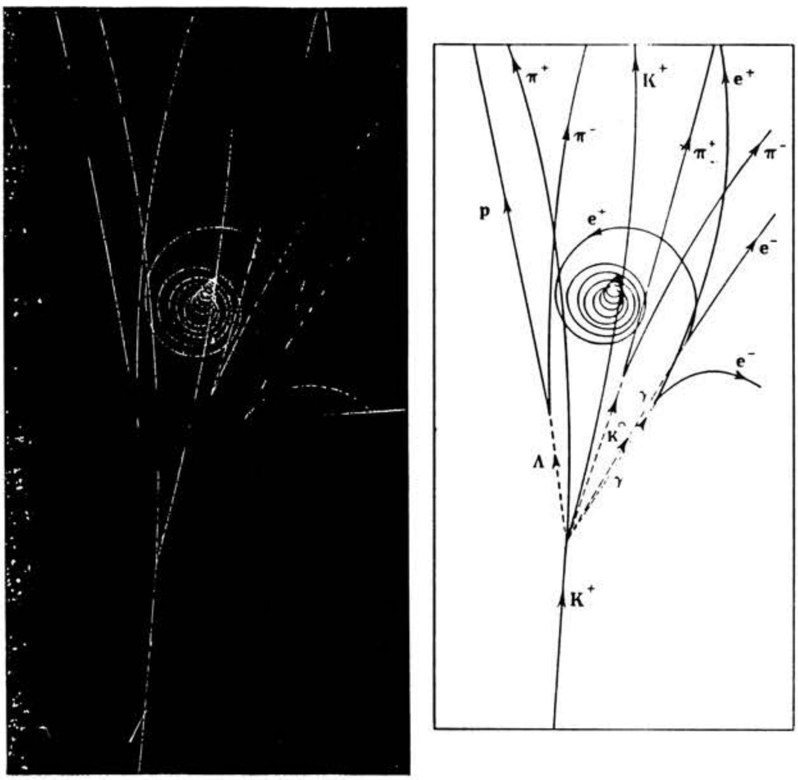


Fig.4

Now let's get down to what the significance of the development of the bubble chamber was. What you see in the next view graph is a bubble chamber picture which has been cleaned up from a hydrogen bubble chamber that operated at the Lawrence Berkeley Laboratory. The point to see here is that you could actually reconstruct the entire event. You can identify the exotic particles in this event by knowing the identity of some of the particles and by using energy and momentum conservation. Because you could calculate the masses of new kinds of particles, you could discover the existence of these particles. You can reconstruct everything, using the things you know about physics, namely energy conservation, momentum conservation, and charge conservation. And this is what was done.

EVENT FROM LBL HYDROGEN
BUBBLE CHAMBER



$K^+ + p \rightarrow$
$\pi^+ + \pi^0 + K^+ + K^0 +$
subsequent
decays and interact

$\Lambda^0 \rightarrow p + \pi^-$
$K^0 \rightarrow \pi^+ + \pi^-$
$\pi^0 \rightarrow \gamma + \gamma$
$\gamma \rightarrow e^+ + e^-$
$\gamma \rightarrow e^+ + e^-$

Fig.5

Then in 1964, the quark model was proposed. Initially, it had three types: the UP quark, the DOWN quark and the STRANGE quark. Strangeness was a new quantum number that had been independently proposed by Kazuhiko Nishijima and Murray Gell-Mann to resolve some experimental paradoxes. All of the quarks had a spin 1/2. But they had a very peculiar property which was very surprising and very troubling. They all have fractional charges and no particle in nature had ever been found with a fractional charge. The UP quark has a charge +2/3, the DOWN quark is -1/3 and the STRANGE quark is -1/3.

QUARK COMPOSITION

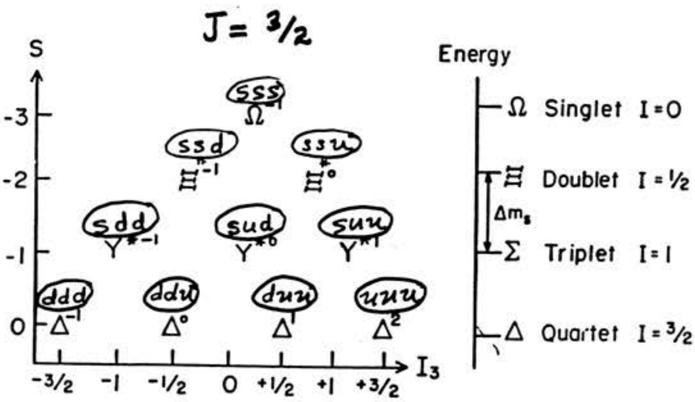


Fig.8

Now the proton, you see, is made up of 2 UP quarks and a DOWN quark, giving the proton a charge +1; and the neutron is made up 2 DOWN quarks and an UP quark, giving a charge 0. You see that's how it was put together. There were some other features that were put in, but that was the basic idea.

You see the thing that is really beautiful about it and why the quark model had relevance was that these families now were believed to be composed of quarks in patterns with a beautiful symmetry. That is, the symmetries of the families were generated by the quarks. For example, this particle here furthest to the left is composed of 3 DOWN quarks, the one furthest to the right is 3 UP quarks, and the particle at the top, the omega minus, is 3 STRANGE quarks. Every particle in between is a mixture of the three kinds of quarks in a very well defined way. So it was a nice picture, but the question was Are quarks real?

What do physicists do to find out if something is real? They will look for it. After all, that's how you find out if something is real. Can I really find it somewhere? Well, there were many attempts to find these quarks. There were attempts to find them at accelerators, in the cosmic rays, and in the terrestrial environment - in mud, seawater, anywhere. Not a quark was found. To many physicists this was not surprising. Fractional charges were considered to be a really strange and unacceptable concept, and the general point of view in 1966 was that quarks were most likely just mathematical representations - useful but not real.

But what did physicists think the proton and neutron looked like? What was the picture of the structure of the proton and neutron in that era? Well, it actually was equally strange, and in a certain sense even stranger. There was a point of view at that time called nuclear democracy, that is the bootstrap model. The idea was that the proton was made up of the neutron plus a positive π meson plus any other particle that will give the proper quantum numbers. A neutron was made up of a proton plus a negative π meson plus other appropriate particles. So all particles were made up of other particles. It's as if somebody said each of you in this auditorium is a composite of everybody else in this auditorium. Now that is a very strange point of view, but in quantum mechanics that is something you can propose for particles. So that was the point of view at that time; and when you look at the structure of such particles, they will have diffuse sub-structures with no elementary building blocks. They are a blob of charge that is very smooth and diffuse That was the picture of the proton and the neutron and all other particles in those days.

What did Gell-Mann, who is the father of the quark model, say about quarks at that time ? He said the ...." idea that mesons and such particles are made up primarily of quarks is difficult to believe.... The probability that the meson consists of a real quark pair rather than two mesons or a baryon and anti-baryon must be quite small...... Thus it seems to me that whether or not real quarks exist, the quark and anti-quark we have been talking about are mathematical. "And then he goes on to say,... "if the mesons and baryons (that is, the protons and neutrons) are made up of mathematical quarks, then the quark model may perfectly well be compatible with the bootstrap hypothesis, that hadrons (that is, all the strongly interacting particles) are made up out of one another. " That is the nuclear democracy point of view.

So there was not great confidence about the quark model at that time. There was a physicist at CERN who wrote a book about quarks and ended up with this conclusion:...." Of course the whole quark idea is ill-founded. So far, quarks have escaped detection. " Then he says at the end:...." The quark model should, therefore, at least for the moment, not be taken for more than what it is, namely, the tentative and simplistic expression of an as yet obscure dynamics underlying the hadronic world. As such, however, the model is of great heuristic value. "

There were, however, a few physicists who were real believers. They would not give up the quark model. They persisted in making calculations of applications of the quark model, but few physicists paid attention to them. So that was the situation at the time.

In 1966 there was an important development. The Stanford Linear Accelerator at SLAC was completed and brought into operation. This is a very long high energy linear accelerator for accelerating electrons. Inelastic electron-proton scattering experiments were started in 1967 and continued until 1974 by an MIT-SLAC collaboration, which included Henry Kendall, Richard Taylor, and myself along with other physicists. Conceptually this was a very simple experiment. You would shoot electrons at protons. Electrons would scatter off and many other particles would be produced. You would only detect the electrons and this provided the first direct evidence for quarks. Let me explain how, because the scientific methodology is really quite simple. I will explain it by an analogy.

I give you a fish bowl with a certain number of fish in it and put it in a dark room. I ask you: How many fish are in the bowl ? I also ask that you not put your hand in the fish bowl. But I give you a flashlight. Well, what you would do is turn on the flashlight and look, right? You would see how many fish there are in the fishbowl. That would be the obvious thing to do.

Well, you see, the experiment was basically the same idea. Instead of having a light beam, you have an electron beam. Instead of using your eyes, you use particle detectors. Instead of having a brain to reconstruct the images, you do that with a computer, programmed by human intelligence. And, of course, instead of looking for fish inside the fishbowl, you are looking for what is inside the proton. So it's basically that idea. You are looking inside the proton with the equivalent of a very powerful electron microscope.

To see a small object of size D clearly in a microscope, you must use light that has a wavelength that is considerably smaller than D. The wavelength is the distance between two successive crests of the wave. You can think of the wavelength as being equivalent to the separation of lines on a ruler. If you want to use a ruler to measure the size of an object with reasonable precision, the separation of these lines should be much smaller than the size of the object.

According to quantum mechanics, electrons, as well as other particles, have a wavelength and this wavelength decreases as the energy of the particle increases. In an electron microscope, electrons are accelerated to sufficient energy to have much shorter wavelengths than ordinary light. This is why electron microscopes can be used to "see" much smaller objects than optical microscopes. So the MIT-SLAC experiments utilized the equivalent of a very powerful electron microscope. The Stanford Linear Accelerator delivered a high intensity beam of 20 billion electron-volt electrons, which provided an effective magnification 60 billion times greater than that with ordinary light. One could measure a size that was about 1/20 the size of a proton. This was necessary because otherwise you couldn't see what is inside the proton. The proton is about a hundred thousand times smaller than the atom, having a radius of about 10^{-13} cm.

This is the picture of the Stanford Linear Accelerator. It is two miles long and you can see there's a road going over it. The electrons are bent into three beam lines. These are the two experimental halls. The experiment was done in the larger of the two halls. The electron beam is bent and it enters this hall which houses the experimental apparatus, which consisted of two large magnetic spectrometers.

Here is a picture of the spectrometers . This is the 20 GeV spectrometer (a GeV is one billion electron-volts). Here is where the beam comes in, here is the target, here is the 8 GeV spectrometer and here are the rails that run around the pivot, on which the spectrometers can be rotated. These were large and very heavy devices. The 20 GeV spectrometer weighed over 3000 tons.

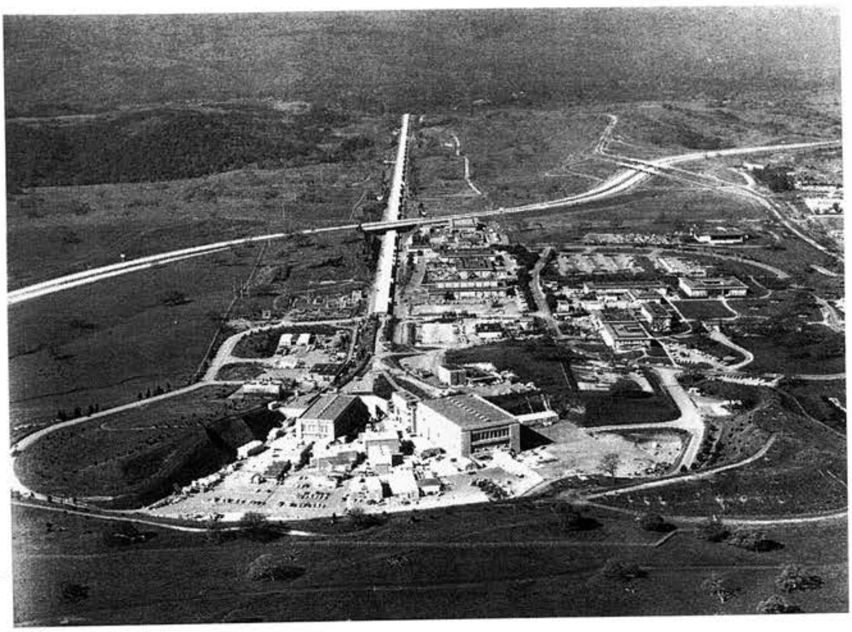


Fig.9

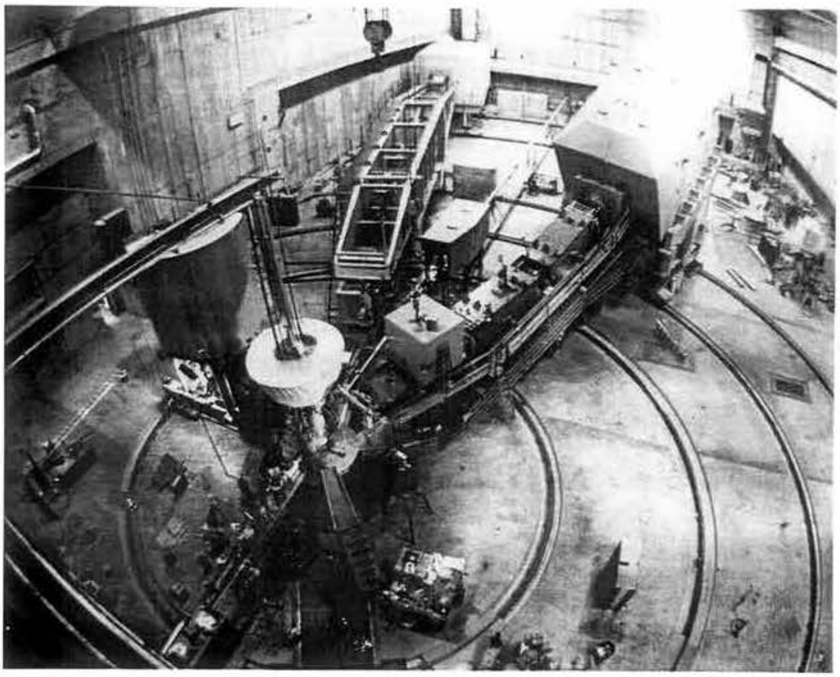


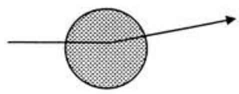
Fig.10

Now what are the characteristics of scattering that you would expect on the basis of these two models, the quark model and nuclear democracy? In a certain sense, this is really the crux of the matter from a physical point of view. If you had the old physics where the charge was quite diffuse (you see the upper image of the model of the proton in the 60's) you would expect the particle to come in and not be deviated too much because the charge is smeared out and there's nothing hard inside to really scatter it very much. The incoming particle comes in and goes through the proton without too much deviation. But if you have constituents inside the proton, then occasionally a particle comes in and scatters with a large angle from one of the constituents, as you can see in the lower image. The observation of a large amount of large angle scattering would imply much smaller objects inside the proton. So you look for the scattering distribution to see what the structure in the proton is, and this is how the experiments were analyzed. I want to show you what was found.

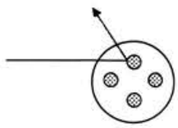
Here in this view graph we show the dependence of the probability of scattering on a quantity that is proportional to the square of the scattering angle. The top curves here are the measurements. This rapidly falling curve is the type of distribution you would expect from the old physics. And you see the difference, about a factor of a thousand, between what the old physics would have predicted in scattering probability and what the experiment found at larger angles.

Scattering

From Diffuse Substructure

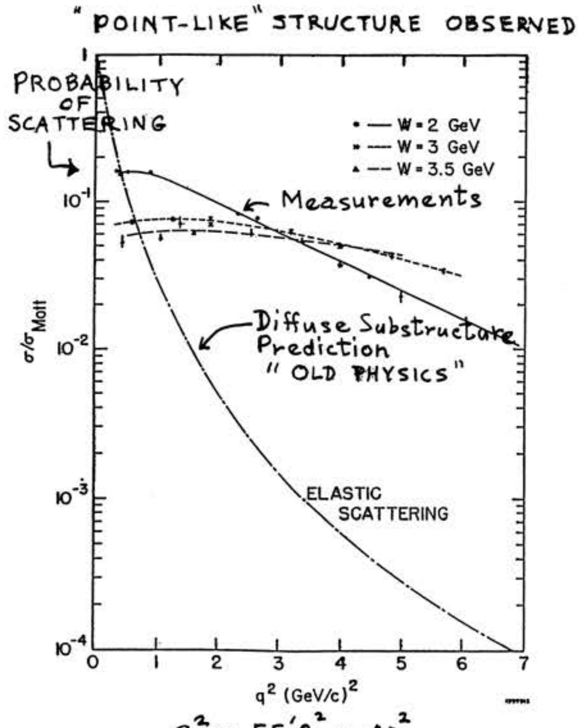


From Constituent Substructure



* **Large Angle Scattering Implies Smaller Objects Inside Particle**

Fig.11



$q^2 \approx EE'\theta^2 \approx \Delta p^2$

Scattering at Large Angles Observed

Fig.12

Basically what these measurements showed was that copious large angle scattering was observed. Now, the experimenters went on to try to analyze and reconstruct the images in terms of what was known. How big were the objects inside? The results indicated that they were point-like. They were smaller than could be measured with the resolution of the system. And when we first did this analysis we concluded that, if it behaves in this way, it implies point-like objects inside. But this was a very strange point of view. It was so different from what was thought at the time that we were reluctant to discuss it publicly. In fact when I gave the first presentation of these results in Vienna in 1968, my colleagues asked me not to report that the proton looks like it has point-like objects inside. To say such a thing would have made us all look as if we were somewhat deranged, and so I didn't say it.

It turned out that Professor Panofsky who was the Director of the Stanford Linear Accelerator gave the plenary talk and he inserted the statement that "....theoretical speculations are focused on the possibility that these data might give evidence on the behavior of point-like structures in the nucleon." (Nucleon is the generic name for the proton and neutron.) So he made this surprising assertion. But we, as young assistant professors at that time, felt we could not. So that's how it was first announced to the world, but nobody really believed it. It was considered a very bizarre point of view. Theorists were very enterprising and they produced in a short time a large stack of theoretical papers trying to explain these new results in terms of models that employed the old physics.

None of them really worked, and that was a problem because you see many attempts were made. If this were a physics seminar, I would tell you all about these old models but it is not important for today's talk. These models were ultimately tested experimentally and they all failed in one aspect or another. None of the traditional points of view explained the surprising electron scattering results. However, the quark model was not generally accepted. So what could explain these results? That was really a puzzle. It was a big puzzle.

But there was one theoretical contribution which helped resolve the whole controversy. It was made by Richard Feynman with his development of the Parton Model. I want to say something about this approach because it played such a crucial role. When he came to SLAC in August of 1968 he was already working on the Parton Model. What was this model? He was working on the problem of protons scattering from protons. He described the proton as being made up of parts, which he called partons. He did not know what the parts were, but he analyzed the scattering in terms of. the parts of one proton hitting those of the other. When he came to SLAC, he heard about the electron scattering results. He talked to a number of people there.

He became excited about these results and he quickly concluded that these experiments provided the perfect test of the Parton Model. Overnight he wrote down a set of equations which became the basis of resolving this problem, establishing a framework for analyzing the electron scattering results and all subsequent measurements. He came back to SLAC the very next day with the results. It was a very exciting weekend and I was fortunate to have been there at the time.

And what is the Parton Model as applied to electron scattering? Well you know, it's really not all that different from what I mentioned earlier with regard to point-like constituents in the proton. But Feynman was a great and highly respected theorist who could get away with proposing such an unorthodox view. His idea was that there are point-like objects in the proton called partons. We didn't know what they are but they are bound. The electrons scatter from them and the partons recoil and interact internally producing known particles. So the partons don't come out, but they produce pions, K mesons and everything we've observed in the laboratory. If the partons are point-like, there is a large amount of large angle scattering, which I pointed out earlier in this talk.

The Parton Model was also consistent with all the kinematic behavior that was observed in the experiment. There were some technical issues which I can't discuss because they are too complicated. One such issue was a kinematic behavior called scaling, which had been proposed by Bjorken and was observed experimentally. This model explained scaling behavior and provided a physical interpretation of it. But the central question was: What are the partons? Are they quarks? At that time he wasn't willing to say what they were. He just said that this is a way of looking at the problem.

Now the question is: How do we show that these little objects inside the proton are quarks? Well, we have to show two things: They must be spin 1/2 particles and they must have fractional charges consistent with the quark model. Those are the requirements. If you don't show those, you haven't proven anything. Well we could actually show what the spin was in a very straightforward way early in the program. It was a hard experiment but we could do it. The idea is that you make a comparison of forward scattering and backward scattering. It turns out that backward scattering has a bigger component of magnetic scattering, which depends on the spin of the constituent from which the electron scatters. You could actually measure the spin of whatever is scattering electrons in the proton. In this view graph you see the predictions for spin zero constituents, and those for spin 1 would be way up here. Now obviously the errors on the experimental points are large. It was a hard experiment because of the radiative corrections, but the results are clearly consistent with spin 1/2. So if there were constituents in the proton, we knew at that time they were spin 1/2 particles. Half of the problem was over. But fractional charge was a much more difficult problem; and to really resolve that problem another type of scattering had to be brought into the picture. Neutrino scattering had to provide the answer. And let me explain why.

Comparisons of forward and backward scattering answered the question: *What is the spin of the proton's constituents ?*

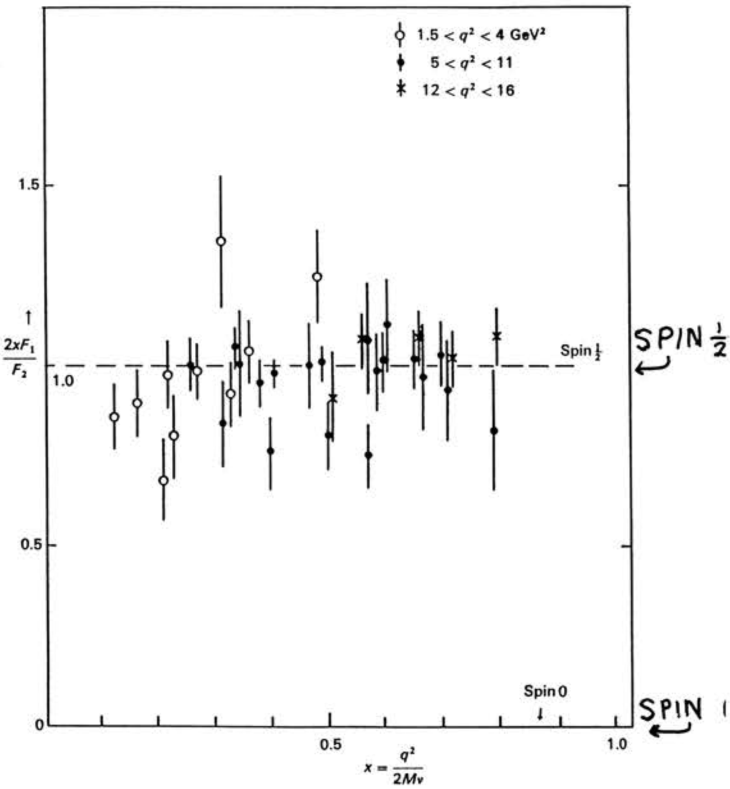


Fig.13

First of all, what are neutrinos? Let me say a few things about neutrinos. Neutrinos basically are particles which are almost ghost-like. They have no mass or a very small mass, they have no charge and they barely interact. A recent experiment in Japan, Super-Kamiokande has recently shown that at least one neutrino has a very small mass. And the preliminary data of a second experiment in Japan, K2K, using a different approach appear to confirm this result. Neutrinos interact so weakly that a 100 billion electron-volt neutrino, has a mean interaction length in iron of 2.5 million miles.

So doing experiments with neutrinos means that you have to use lots of neutrinos, have a huge target and have a great deal of patience. Neutrinos are produced from particle decays but we won't get into the details of that. The ironic thing is that the first results came from the Gargamelle bubble chamber at CERN which was able to make these measurements. The first thing the bubble chamber showed was that the scattering probability for neutrinos, as a function of energy, went up as a straight line. This demonstrated that the neutrino measurements were also finding point-like structure in the protons. And comparisons of electron and neutrino scattering later confirmed that the point- like constituents of the neutron and proton have the fractional charges of the quark model.

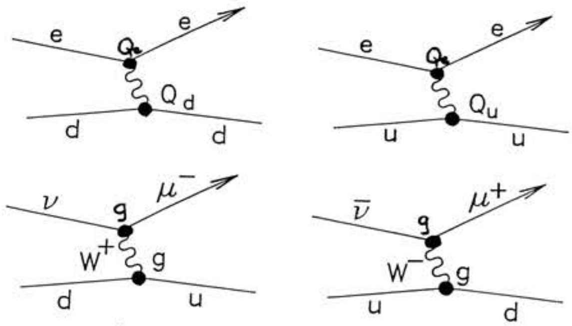
So how do you find out about the charges of the constituents by making such comparisons of the scattering? Now this is actually a simple argument although it may seem a little complicated.

In this view graph you see here an electron scattering from a DOWN quark, and here from an UP quark. Now the force that causes the scattering of the electron by the quark has to depend upon the charge of the quark and the charge of the electron. So the force is proportional to the product of these two charges. If we have neutrino scattering, as shown below, the complication is that the neutrino turns into a muon and exchanges a particle called the W particle. But let's not worry about that. The point is that the force between the neutrino and the quark in this scattering results from effective charges associated with the so-called weak interaction. This effective charge is not an electric charge. We call it a weak coupling constant, g. The force that causes the scattering here is proportional to g^2. Therefore, if you take the ratio of neutrino scattering to electron scattering, what you're getting here is proportional to g^4 divided by the square of the charge of the electron times the square of the charge of the quark.

So the point here is that by measuring the ratio of these scattering probabilities and properly normalizing it, you can get information about the charge of the quark. And that's all there is to it. That was done and the result comes out this way. The ratio of the scattering probabilities properly normalized comes out to be 2 over the square of the UP quark charge plus the square of the DOWN quark charge. And if you put the values of the quark charges into this, this ratio turns out to be 3.6.

When the experimental value of this ratio was evaluated by comparing the MIT-SLAC scattering results with the CERN bubble chamber results, the answer turned out to be 3.4 +/- 0.7. Of course, the error was large because of the great difficulty of measuring neutrino scattering in a bubble chamber, but the agreement was remarkable. If quarks did not have these fractional charges, you would not get close to this number. It was a remarkable agreement and the idea that there were quarks inside the proton and neutron became something that one could not deny. Let's keep a scorecard here, which is seen in the next transparency.

COMPARISON OF ELECTRON AND NEUTRINO SCATTERING



Scattering is due to forces

Electromagnetic (E-M) forces → e scattering

Weak forces → ν scattering

E-M forces $\sim Q_e Q_q$ Weak forces $\sim g^2$

$$\frac{\text{Prob}(\nu\text{-}q \text{ scattering})}{\text{Prob}(e\text{-}q \text{ scattering})} \sim \frac{g^4}{Q_e^2 Q_q^2}$$

g, Q_e known Determine value of Q_q

Fig.14

COMPARISON OF MODELS AND MEASUREMENTS

	SPIN	FRACTIONAL CHARGES	"POINT-LIKE"
Boot-Strap (Nuclear-Democracy) $p = n + \pi^+ + \ldots$ $n = p + \pi^- + \ldots$	½ & 0 + …	no	no
Quark Model $p = u + u + d$ $n = d + d + u$	½	yes	yes
EXPERIMENT	½	yes	yes

Fig.15

If we look at the bootstrap- nuclear democracy model, we have spin 1 and spin 0, but for the quark model we have spin 1/2 and experiment gives spin 1/2. Fractional charges? For the bootstrap- nuclear democracy model, no; quark model, yes; experiment, yes. Point-like structure? For the bootstrap- nuclear democracy model, no; quark model, yes; experiment, yes. We cannot escape the quark model. There was no way that the old model satisfied the experimental results.

What the picture of the proton becomes in this case is what is seen in the next view graph. This is the proton. Here are 3 quarks and there's another feature present called color which I won't go into. The term color represents the source of the strong force, which is responsible for holding the quarks together in the proton. There are 3 colors and each of the quarks in the proton has a different color. And you see these wiggly lines here; these represent the forces which hold quarks together. The forces are due to the exchange of particles called gluons, and occasionally a gluon will actually make a quark, anti-quark pair and they will come together and form a gluon again. All of these together constitute the proton.

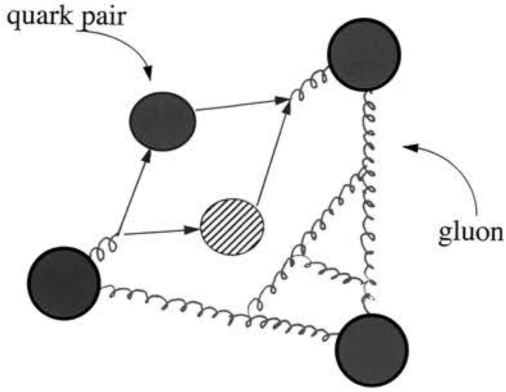
One of the interesting features about gluons is that they interact with one another. A gluon will attach itself to another gluon. You see a photon will not attach itself to another photon but a gluon has this feature and this results in some very unusual behavior of the strong force. So this is what a proton looks like. The nuclear democracy model faded away between 1974 and 1980. There were some die-hards who didn't want to give up but by 1980 they constituted a very small minority. By that time all theory and experiments were based on the quark model.

So far all the experiments that have been done up to the present time are consistent with the quark model, so let's talk about the properties of quarks as we know them now. It turns out we now have six different kinds of quarks. Stable matter is made up of only two of these, the UP and DOWN quarks; but in addition there are the STRANGE, CHARM, BOTTOM, and TOP quarks. The TOP quark was discovered only a few years ago. As you can see the UP and DOWN masses are quite small, just a few MeV. The STRANGE quark mass is about 150 MeV, the CHARM quark 1.5 GeV and the BOTTOM 5 GeV. The TOP quark is enormously heavy. It's about 174 GeV which means that it's heavier than about 185 protons. This is a great mystery. Nobody understands why there is this tremendous variation in quark masses.

All the quarks have fractional charges, 2/3 or -1/3. All have spin 1/2 and all have baryon number 1/3, which means that it takes 3 of them to make up a proton or any proton-like particle.

One question remains - What is the size of the quark? Well, the size of the quark is still smaller than we can measure. We presently measure it to be smaller that 10^{-17} cm in size. So we say it's point-like.

MODEL OF NUCLEON



"Nuclear Democracy" fades away
1974 -1980

Fig.16

Properties of Quarks

Flavor	u	d	s	c	b	t
Mass	~few MeV	~few MeV	~150 MeV	~1.5 GeV	~5 GeV	$\gtrsim$ ~~90~~ 174 GeV
Charge Q	2/3	−1/3	−1/3	2/3	−1/3	2/3
Spin	1/2	1/2	1/2	1/2	1/2	1/2
Baryon Number B	1/3	1/3	1/3	1/3	1/3	1/3

for anti-quarks Baryon Number → −B
Charge → −Q

SIZE OF QUARK $\lesssim$ ~~2~~ 1 $\times\ 10^{-17}$ cm

Fig.17

We don't necessarily believe that it's a point, but as far as our tools of measurement can go, we only see points. Now 10^{-17} cm is an upper limit of what its size could be. Let's think about what that means. That's an exceedingly small size. If we took a carbon atom and expanded it to the size of the earth, a quark would be less than a quarter of an inch in comparison. And that's the upper limit of its size.

Now the size of electrons has been measured and they have the same upper limit for their size. So there's a very strange point of view that's emerging from these results. The little nuggets of matter, the quarks and the electrons, that make up matter essentially occupy no space. We're all empty space. Sorry to tell you that. Because you know if you look at the total volume of an atom and you compare the volumes of all the quarks and electrons in the atom calculated from the upper limit of their sizes, the quarks and electrons occupy an unbelievably small fraction of volume of the atom. It is only about one part in 10^{26}. So the question is, if that's the case, why can't I put my hand through this table? Because after all, these infinitesimal nuggets won't collide when the probability is so small for collision

Well, the reason you can't do that is because of the force fields. The force fields basically give us the sense of continuous matter. They occupy all of that empty space. And therefore if I try to put my hand through the table, it's repelled by the force fields in this table. The nuggets in my hand are being repelled by the force fields of the nuggets in the table and vice-versa. So that's the concept of matter in the modern view.

Now you might say to me that I am trying to fool you in a certain sense, because one of the reasons we didn't believe in quarks in the first place was that a quark had never been found. So you might ask me, Has a quark been found? If you ask me that, I have to say no. So why do I believe in quarks?

Well it turns out there was a theory called quantum chromodynamics proposed in 1973, which showed that because of the strange properties of the gluon field, quarks are most likely permanently confined inside the proton and other particles. Remember I said gluon fields connect to one another, unlike photon fields. That property produces a very unusual force, a force which actually tends to get somewhat larger or at least remains constant as you pull 2 quarks apart. So you realize what that means. It's like a spring. When I try to pull a spring apart, the force increases. If this is truly the force field, the quarks are permanently confined. If I try to pull one quark to infinity, which is where the quark can be free, I have to supply an infinite amount of energy, which is clearly impossible. This means that the quark is not free and can never be free. Now this is not proved mathematically; but every indication from experiment and theory indicates that this is the case, and theorists are trying to develop mathematical proofs. Now if you have two quarks sitting side by side separated by 10^{-13} cm the force between them is roughly of the order of 15 tons. This gives you an idea of the strength of the forces between two quarks.

If I try to pull two quarks 1 cm apart, I've got to expend an energy of 10^{13} GeV. If I try to make an accelerator capable of putting that amount of energy into this system of two quarks, that accelerator, if built on the basis of current technology, would have to be comparable in size to our solar system. So I can't do that.

But what happens if you take a quark and anti-quark and you try to pull them apart? After you have separated them by an infinitesimal distance the force field breaks and an anti-quark and quark form at the broken ends of the force field. The original quark pair constituted one meson and after the break occurs you have two mesons. If you keep on doing that, you have three mesons and so on. This is the way particle production occurs in this theory. So it's a very unusual theory, a very interesting theory. There are many questions still to be answered.

Do quarks have finite size and if so, how big are they? Now if they have a finite size they most likely have an internal structure of some kind. This structure would mean that maybe something else is inside of them. So there could be another layer of matter inside quarks; but there's one problem with that and I'll tell you what the problem is. This problem doesn't mean it's impossible, but it makes it seem very unlikely or unreasonable. The problem arises because the quark is so small. Quantum mechanics says that all particles have an associated wave length that is related to the particle's momentum. The larger the momentum, the smaller the wave length; and if you want to confine a particle within a certain volume, the wavelength of the particle has to be comparable to the size of the volume. The smaller the volume, the smaller the wavelength, and the higher the kinetic energy of that particle inside. So if you look at how small the upper limit of the size of a quark is, any smaller particle inside of it would have to have an immense kinetic energy, actually more than 10,000 times greater than the kinetic energy of a quark in the proton. And the greater the kinetic energy of the particle inside the stronger the force has to be to hold the smaller particle inside. If you estimate the force required to hold a particle within the volume of a quark, if the quark were as large as the upper limit of its size, it turns out you get a force that is about 100 million times greater than the strong force. And the strong force is the strongest fundamental force that we know of in nature.

So the forces inside would be absolutely immense if you had something inside in the quark. This doesn't mean that this internal structure of the quark doesn't exist, but that it would be mind boggling if it did. But there is a possibility that it does, and that there are new types of forces and particles in nature of which we have no knowledge.

The only way to search for this structure is to have higher energy available for further studies; because as I said before, in experiments probing the structure of particles, the effective magnification grows with energy. Fortunately, there is a new collider being built at CERN called the Large Hadron Collider, which will be completed in 2005. It will produce a total energy of 14 trillion electron volts. The highest energy we have now is about 2 trillion electron volts. Given the increase in beam energy and intensity, the Large Hadron Collider will increase the effective magnification by a factor of 10 or greater. So one will be able to push the limit of the size of the quark down to about 10^{-18}cm or lower - or find new structure - with this future collider. But you see there is a problem here. For every factor of 10 smaller in size that you probe, you must have a factor of 10 more in energy, which makes it very difficult to continue the probe beyond the Large Hadron Collider without the development of new types of accelerator technology.

But who knows? Maybe something unexpected will be found and maybe in the year 2007 somebody will report that there is a new layer in the structure of matter. That would be very exciting.

In concluding this lecture, I would like to make a few personal remarks. What attracted me to physics was a deep curiosity about the wonders of nature and a desire to learn as much as I could about how the world works at its most basic level. So I want to say to the students in the audience, if you have a deep curiosity about nature, if you have a sense of awe about the magnificent wonders of the universe, I strongly recommend a career in science. You will find, as I have, that there is great pleasure in learning about how the world works - that phenomena which seem like magic can be understood on the basis of fundamental laws and principles. And exploring the unknown is a very exciting challenge. There is immense joy in finding out something new, something that no one else has ever known before. So study science, nurture your curiosity, follow your imagination, and perhaps someday you will be standing here talking about a new discovery. Thank you.