

THE STORY OF QUARKS*

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It's a pleasure to be here discussing quarks with a distinguished audience from our leading Singaporean researchers. I've traveled here several times and I've enjoyed every visit.

The quarks are a very important discovery, as Professor Phua mentioned. But I will not actually adhere to the scheme of describing the story. Instead of concentrating on the story, I propose to concentrate on the facts. I'll try to present a picture of how we look at the quarks today and a little bit of what we know about them.

In elementary science classes, you learn that a great deal of matter is in the form of atoms, with a central nucleus, and electrons going round. The nucleus is composed of protons with electric charge $+1$ in suitable units and neutrons with electric charge 0 . For a long time, it was thought that protons and neutrons would be like electrons — elementary, and not composed of anything simpler, but we know now that that's not true. In fact, the neutron and proton are made up of quarks.

It's an obvious name for the fundamental constituents of strongly interacting matter. Let's listen to that sound, quark, just the right sound. And as to the spelling, we got that from James Joyce's *Finnegans Wake* "Three quarks for Muster Mark!" The idea of the proton and neutron being not elementary, as we so long thought, took awhile to catch on, but now I think it's generally recognized that it's correct.

It's actually not hard to see, when you look at not just the neutron and proton states, but at the higher energy states of these corresponding particles which are

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known as baryons. So you have not only the neutrons and protons but a little bit heavier you have the Λ particle and a little heavier than that you have the three Σ particles and so on and so forth.

The states that lie relatively low in energy or mass, you remember the formula $E = mc^2$, so we can talk about rest mass (m) or rest energy be the same, except for the factor of c^2 . The easily accessible baryons are described in terms of three flavors of quarks — the three flavors that are light and have relatively small masses. And then there are also three heavier flavors of quarks, which you can't get at without a very high energy accelerator. I'll talk mainly about the light quarks, the ones that we run into more often in most theory and experiments.

The three light quarks are called s , d and u — singlet, up and down. The d and u are very light indeed and have very very low mass, and the s quark is somewhat heavier. More recently discovered, and as I said, more difficult to access, are the heavy quarks. Three more “flavors,” called b , t and c , or bottom, top and charm. When we look at the whole set of six “flavors,” three of them with charge $-1/3$ in conventional units where the proton charge is 1, and t , c and u with electric charge $+2/3$ in units of the proton charge, we have the six “flavors” altogether, the three heavy ones and the three light ones. They may be compared to the six flavors of lepton, including the electron, the muon — which is a heavy electron, and the tauon — which is the still heavier electron. For each electron, there is a neutrino. We know now that those neutrinos are distinct from one another. So there is the three charged leptons, e , μ and τ , and three corresponding neutrinos with 0 charge.

So we have these interesting patterns of six states in each case. Six for the leptons, six for the quarks. Why is that? A very good question for which we don't know the answer. While we know more about this fascinating and fundamental subject, we hope to understand better why the patterns resemble each other.

Here I repeat that the six flavor pattern is not really understood today, but we hope to understand it sometime in the future. And we don't understand why the flavor pattern is approximately the same for leptons and for quarks, but it's very symmetrical.

Here we see the diagram of the neutron and the proton (Fig. 1) and the set of the excited states — the Lambda, the three Sigmas, and the two Xi particles. It is fairly straightforward that these can be thought of as made up of three quarks. The u and d quarks make up the neutron and proton. When we go over to the Λ particle, one of the quarks changes to an s . Same for the Σ , when we go to the Ξ , two quarks become an s quark.

That is perfectly reasonable. We see why these states are heavier than these, and these are heavier than these, because they contain s quarks, which are heavier than the u and the d . Then theory tells us that there is a sum rule for the masses. The approximate sum rule, $\frac{M_{\Xi} + M_N}{2} = \frac{3M_{\Lambda} + M_{\Sigma}}{4}$, N : neutron or proton. And it works — theoretical formula compared with observation — it works very well.

Then there's another set of states, a different pattern, starts out with the Δ particles which have the charges — 1, 0, +1 and +2. They are made up of d and u

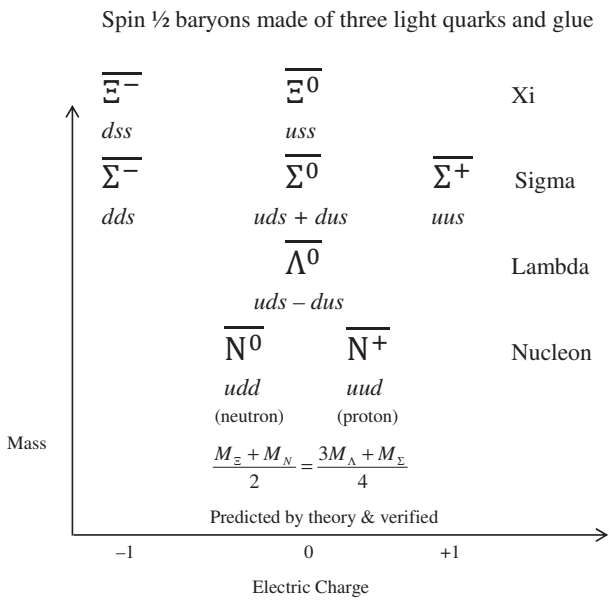


Fig. 1.

quarks ranging from ddd for Δ^- , all the way to uuu for Δ^{++} . If we substitute one s quark, we get the Σ . If we substitute two s quarks, we get the Ξ . If we substitute three s quarks, so that we have just three s quarks altogether, then we get the Ω^- .

The Ω^- has some spectacular properties experimentally. It decays in a sequence, in a cascade sequence it decays: $\Omega \rightarrow \Xi$, $\Xi \rightarrow \Lambda$, $\Lambda \rightarrow$ proton.

The way it was proposed was the following: there was a meeting in 1958, an international meeting on particle physics at CERN near Geneva, Switzerland. I attended that meeting and I heard presentations about excited states of the baryon, including one that fitted this pattern: $\Sigma^-, \Sigma^{*0}, \Sigma^{*-+}$. I said to myself “Gosh! If one of this set of particles is like this, then the masses are equally spaced. This minus this, is the same as this minus this, is the same as this minus this.” And that’s what the speaker was saying — he was saying they just discovered an excited state with a suitable mass for this. That meant that had to be the final one, the Ω^- with the spectacular properties had to exist, and we could predict its mass quite accurately.

So I got up and told the international meeting about that, and two young experimentalists at the Brookhaven National Laboratory in New York State, Long Island, came up to me and asked me to write a recommendation that they be funded for searching for this particle, the Ω^- . I seized a napkin at the CERN cafeteria and scrawled on the napkin a request for funds for these two experimentalists, and handed it to the director of Brookhaven, who happened to be there also. He granted the request, they started their procedure. It took them two years and scanning 2 million feet of film to find an event that corresponded to a decay, a cascade decay of the Ω^- .

Not only did they find one — they found two — the same day after waiting for two years, representing two different decay modes of the Ω^- .

The masses came out in accordance to that sum rule formula. Everything seemed perfect. Still, we were not describing these states in terms of quarks, it would have been so simple. We had the mathematics right, but the very simple way of stating the mathematics would be that these things were made of three quarks. It was not, at that time, the way we talked about it.

It took a few years, then came this date which was very important for me — February 1, 1964. That's the day that the discovery of the Ω^- was made. It was also the day when my letter to the journal *Physics Letters B* about the quarks was printed. We can think of that as a time of transition — before quarks to after quarks.

Here's how these particles look in terms of quarks. Four states, with charges ranging from -1 to $+2$ — ddd , ddu , duu and uuu — then there's a strangeness -1 standard particles, with one s quark, then there are these with two s quarks, and finally the Ω^- , which was composed of three s quarks. Looking at it in terms of quarks makes these things very very simple, very easy to understand. It is also very reasonable that the mass differences should also be the same, equally spaced states in energy or mass.

Now we have to mention another property of the quark which was not understood for a number of years. That is, that the quarks carry besides the flavor label, another label which is called "color." It has nothing to do with regular color — it's just part of a joke — nevertheless, we use that name "color." Primary colors for mixing lights can be thought of as red and blue and green. So we can think of these quarks as being red or blue or green. It is designated by RGB. It's just a three-value variable RGB. Colors is just a nickname. It's very important that the quarks bear this additional label. So the number of states is no longer two for particle and antiparticle: six plus six through six flavors, giving 24. Instead, we now have two for particle and antiparticle, three, for the three colors times the six flavors, plus one, for the leptons, and their six flavors. So we get 48 states instead of 24, when we include the color.

Now this color variable turns out to be very very important. It's not just a label, it's the analogue for the strong interaction of electric charge for the electromagnetic interaction. The whole basis of the dynamics of quarks has to do with color. The color variable acts like the charge. But this is a more complicated kind of charge. Also, just as the electromagnetic interaction is mediated by photons with quantum electromagnetism. So, here the strong force that binds the quarks together acts on color, and is mediated by gluons, which are the quanta of the strong color force, just the way photons are the quanta of electromagnetism.

We see that analogy now. We have gluons instead of photons. We have strong interactions that include electromagnetism, and the gluons are the quanta of the strong color force. That made it possible to write down a theory — a serious, quantitative, exact proposal for a theory which we call quantum chromodynamics.

Again, making use of that joke about colors. “Chromo,” of course, comes from the Greek word “color.” So, QCD is the field theory of quarks and gluons, and it accounts very well for the strong interactions and for the strongly interactive particles — generally accepted as the correct theory of quarks and gluons.

Here, I digress to describe some work that must take place in the future. We look forward to a unified theory of quantum electrodynamics, the theory of the weak force, and the theory of the strong force quantum chromodynamics, all unified together in a single coherent theory. We don’t quite have that, but we have some hints as to how to get it, and my colleague Harald Fritzsch among other people has worked on this idea. When that’s achieved, there will be corrections to quantum chromodynamics coming from the rest of this unified theory.

Beyond that, there is a still further unified theory that we all hope to see some day, which incorporates not only the strong and weak and electromagnetic interactions, but also, general relativistic Einsteinian gravitational altogether the same unified theory. That’s a sort of holy grail for particle physicists. Everybody would like to discover and understand that hypothetical theory that would unify all the forces in a single description. We don’t have it, but we look forward to having it someday.

When it comes, it will contain, of course, corrections to QCD. So QCD is not in that sense a perfectly final theory, there will have to be some final corrections to it from the unification. Even the minor unification including strong electromagnetic and weak interactions — even that will produce changes in QCD. But for the moment, the level of accuracy in which we work today, QCD is the complete theory of the strong interaction.

Now I’m sometimes asked on occasions like this: “How did you come up with this idea of quarks? Was that very difficult?” My answer is: “It was not difficult at all! It was almost obvious that the neutron and proton in their excited states were made of quarks.” You start to look at the patterns and it’s indicated very clearly by the patterns. So that was not the difficult step. What was tricky was to get rid of three false principles which inhibited our understanding. These are three slogans, not all of them false, that made it difficult to utilize the quark idea.

The first one is that the neutron and proton are elementary and they are not composed of simpler things. Everybody knew that, and there was only one problem with it: it was false. The neutron and proton are made up of simpler objects, namely the quarks.

The second wrong principle was that the elementary particles cannot be trapped inside things like the neutron and proton, never to emerge singly, to be handled singly. Not to emerge as to be handled in quarkonics industry. There is no quarkonics industry. Well, it’s true, unfortunately, that proposition is false, also. The quarks are confined inside color-neutral objects like the neutron and proton, not to emerge so as to be used in industry.

The third wrong principle is that elementary particles have to have integral electric charges in units of the proton charge: +1, 0, -1, +2 are alright, but

$+2/3$ and $-1/3$ are not alright. It's another interesting principle, and again, false.

In fact, the quarks have fractional electric charges: $+2/3$ and $-1/3$, and the antiquarks $-2/3$ and $+1/3$. It's not unheard of for theory to run into this kind of thing. It happens from time to time.

Here again I mention that there is no quarkonics industry. If the colorful particles were not confined, there probably would be a quarkonics industry. They could probably mediate thermonuclear reaction to give thermonuclear control and thermonuclear energy, it would be very useful. In fact, they don't because they are confined.

So, here I mention another case of a false principle that impeded progress. Back in the 1940s and 1950s, and earlier, American students of geology were taught by their geology professors that continental drift was wrong and impossible. Many schoolchildren have looked at the maps of the continents and see that they fit together, like a jigsaw puzzle. These bright children asked their teachers: "Isn't that important? Were those continents together at one time?" The teacher, if properly trained in American geology, said: "No, no, no. That's a silly idea, forget it." But of course, it was not a silly idea. The continents were together 200 million years ago when they began to split up into pieces. But the students kept being taught for a long time that continental drift was wrong. Finally, in the early 1960s, the evidence for the continental drift became so strong, and the appeal of the new theory of continental drift — called plate tectonics — canceled out all those years of instruction in the wrong principle.

Finally, geology teachers taught that continental drift was okay, provided it fitted in with plate tectonics. Except, I am told, in Harvard, where they held out for another 10 years.

In my opinion, when faced with these arbitrary prohibitions of thinking, one should cultivate the habit of asking "Why not? Why not confine quarks? Why not continental drift? Are you really sure that thinking along these lines is bad?" and so on and so forth. I mention here another case of Dr. Semmelweis, in Budapest in the 19th century, who tried to prevent the spread of puerperal fever, which afflicted mothers and babies. Brand new babies and mothers were dying in enormous numbers in hospitals, and Semmelweis suggested that if the health workers, doctors and midwives wash their hands thoroughly, there wouldn't be a problem. Well, they considered this false and insulting, and nothing was done about it for a number of years. Many mothers and babies died during those years unnecessarily.

Finally, Dr. Lister came along in England and washed everything in carbolic acid, and became Lord Lister, and puerperal fever was wiped out. But it took a while.

So we have to be very careful when faced with these negative proclamations to say "why not?", and make sure that there really is a case against the condemned idea.

In case there's time, I hope you won't be afraid to ask questions. Thank you.