THE NOVEMBER REVOLUTION

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As the name 'revolution' implies, the discoveries of November 1974 were not just additions to our knowledge of Nature. Instead they signalled a change in our understanding of the structure of matter: that the particles in the nucleus of the atom are themselves composite and are made of quarks. This new layer of structure, the quark level, was moreover one for which we have simple equations to describe the forces which act on the quarks. Thus there emerged what is called the Standard Model of the structure of matter and its forces.

Of course this change in our basic understanding did not occur completely overnight. Many of the ideas were there before, accepted by some and doubted by others. As always, there were also plenty of wrong ideas and irrelevant pieces of information. Nor was everything completely in place at the end of 1974. But with 20-20 hindsight we can now see that the different currents of research and ideas converged in those exciting days in November. And within a couple of years afterwards, no one, but no one, would be found writing about this part of physics without at least a perfunctory bow to the Standard Model.

Historical Background

How did we get this new understanding of matter, this new level of structure? We recall that the smallest part of an element is the atom, with a size of about a hundred-millionth of an inch. From experiments done at the beginning of this century, we also know that the atom is composite: it has electrons moving about a nucleus which is about a hundred thousand times smaller than the atom as a whole. The nucleus itself has been known since the 1930s to be made up of particles called protons and neutrons. Much of the elementary particle physics of the 50s and 60s was spent in bombarding protons and neutrons and studying the many other kinds of related particles produced in these collisions. By the end of that period there were literally hundreds of relatives of the proton and neutron known, with additional cousins being found every year. Nobody could regard *all* these particles as elementary.

In 1964 the concept of quarks was introduced: they were to be the building blocks of the proton, the neutron, and all their relatives. And while there was a multitude of these particles known, one only needed three different kinds of quarks in various combinations to explain all of them. Clearly this was an enormous simplification. But there were several problems with the idea and, in particular, what seemed early on to be one major one — no one ever found a quark. Many took them to be just fictitious entities that provided an easy way to predict what would be observed by counting on your fingers (and sometimes your toes), but were then to be thrown away even if you kept the answer they provided.

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As time went on the evidence for quarks mounted. I have already mentioned the successful explanation they provided for the many observed particles (that's a major reason they were invented). This continued as new particles were discovered and added to our catalog. Then came the beautiful experiments done here at *SLAC* on inelastic scattering of electrons from protons and neutrons where, in effect, one can make an instantaneous picture of what's inside the target that carries an electric charge. Sure enough, what was 'seen' inside the proton and neutron seemed to have all the properties of quarks.

There was other evidence from a completely different direction as well: one could predict the sign and relative magnitude of many transitions from one particle into another. I spent a good part of the year before November 1974 working on just this problem. When you get the right answer once or twice it can be just luck, but when it happens 20 times you begin to think that there must be something to those quarks, even if you don't see them as isolated particles.

In short, there was considerable evidence for the idea of quark constituents by 1974. Nevertheless, there were certainly plenty of doubters as to whether they were 'real' or just a useful construct used by theorists without real justification in order to predict the right answer to some experiments.

Strong Interactions

Physics is defined in the dictionary as "the science of matter and energy and the interaction between them." In addition to the structure we study the interactions or, if you like, the forces. In the nucleus there are the so-called strong forces acting between the protons and neutrons. In fact we use the name 'strongly interacting particles' to denote the proton, neutron and related particles which act on each other with this strong force.

Unfortunately, exactly because the force was strong there was no easy way to solve the equations involving it. We mostly know how to treat problems where the interaction is a perturbation, where it only makes small changes. Here the change was big, and trying to add up its effects gives a sum where each successive term is bigger than the last.

In 1972 a theory of the strong force between quarks was written down, called Quantum Chromodynamics or *QCD* for short. As the initials imply, it was closely related to the only previously successful quantum field theory we had, *QED* (Quantum Electrodynamics). In this new theory, the electric charge is replaced by a 'strong' charge called 'color,' and the photon of electromagnetism by 'gluons' which bind the quarks together to form the proton, neutron, and all the other strongly interacting particles.

There was initial evidence for *QCD* in that the predicted rates for some processes picked up factors of 3, which made for better agreement with experiment. It also allowed one to understand both why free quarks were not being produced and why the strong interactions didn't totally mess up the simple results seen in the deep inelastic scattering experiments. In fact, by the summer of 1974 small deviations from the simple behavior had begun to show up in the latest such experiments, in agreement with what *QCD* predicted.

Electroweak Interactions

As we have just noted, our most successful theory has been *QED*, and we have modeled the theory of strong interactions, *QCD*, on it. There is another interaction called the weak interaction which occurs between particles. It is responsible for beta-decay, a particular type of radioactivity, among other things. In 1967 Weinberg and Salam proposed unifying the theory of electricity and magnetism and of weak interactions in a combined theory modeled on — what else? — *QED*.

In the early 70s the theoretical basis of this theory was made much more secure. The experimental evidence also began to build up, particularly with the discovery of so-called 'neutral currents' in 1973. But in some ways this was a mixed blessing in that while some neutral current effects were 'good,' as they were unambiguously predicted by the theory and found, others which were also predicted to be present in a theory with just 3 kinds of quarks were stunningly absent: they are in some cases a hundred million times smaller than if they occurred at the same rate as the 'good' effects.

As the evidence for the Weinberg-Salam theory grew, so did the need to cure this problem. A solution had already been proposed in 1970: add another quark, a fourth, called the charm quark. The theory becomes very symmetric and the unwanted neutral currents no longer appear — they are exactly cancelled. Furthermore, by looking at the predictions of the theory closely, one could even get a prediction of how heavy the charm quark had to be: about twice as heavy as a proton.

November 1974

That brings us to November 1974. All the pieces were there, but somehow very few people aside from two of the original proposers of a charm quark (Glashow, in a conference in Boston in the Spring of 1974, and Iliopolous, at the International Conference in London in July of 1974) were ready to say loudly that we should swallow the whole picture: quarks, *QCD*, the electroweak theory, and, most of all, that there had to be another quark: the charm quark. I well remember the London Conference where I spoke on inelastic scattering and Burt Richter spoke on electron-positron (e^+e^-) annihilation. Because we didn't know of the gigantic resonances hiding in between energies at which *SLAC* e^+e^- data were taken, the theorists were in total disarray. No one revelled more in pointing this out than Burt, who between occasions in which he pushed his own theory of what was happening in e^+e^- annihilation, would point to dozens of different theoretical predictions, ranging from zero to infinity, of what would happen to the rate of interactions as the e^+e^- energy increased indefinitely.

All this came to a happy end on November 11 with the announcement of the discovery of the psi (ψ) at *SLAC* and the same particle, called J, at Brookhaven. Ten days later came the psi-prime, or ψ', the second member of the same family. It's hard now to recapture the excitement in the world of physics. I was a visitor at the Institute for Advanced Study — in fact some claim that great discoveries are only made here when I leave. Everyone discussed the 'new particles' and waited for the latest discoveries, which seemed to come every day. I vividly remember coming back to the Institute from giving seminars in Michigan, and as I walked across the normally staid Common Room having the telephone operator call out to me: "They're trying to reach you from Stanford; they found another particle." That's how I found out about the ψ'.

Why was it so exciting and so significant? First, because the ψ and ψ' and the other particles which are their close relatives are made of charm quarks (and antiquarks). The spectrum of such particles can be studied with great precision and it is just the spectrum you would expect on the basis of quark constituents. We had a stunning example which showed the quark layer of substructure to matter.

Second, the charm quark is relatively heavy and moves comparatively slowly inside the ψ. Finally we had something small: not the strength of interaction, but the quark's velocity. For many predictions we can even take the charm quark and antiquark to be at rest to a good approximation, and make predictions for the properties of the ψ and relations between the ψ and ψ' and so on. In many ways we have here a kind of hydrogen atom of the strong interactions: a problem we can 'solve' as the hydrogen atom was solved by quantum mechanics and whose agreement with experiment gives us confidence in the theory of forces *(QCD)* as well as again confirming the quark layer of matter.

Third, and most obviously, the charm quark's existence fulfilled the need for it in the unified theory of electromagnetism and weak interactions. Not only was it found, but it had the right mass.

Within a year a good part of the spectrum of the system was found, and, in a year and a half, also the particles containing the charm quark in combination with the 'old' three kinds of quarks.

Even more spectacular was the discovery at *SLAC*, in some of the same data, of a heavy partner of the electron and muon — the tau. This new lepton was the subject of some confusion to start with because it was difficult to separate from charm. Because of a pairing of quarks and leptons which we do not understand, an additional lepton meant additional quarks. Sure enough, within a few years the *b*-quark was found, and within the last few months the *t*-quark. Whether this ends the discoveries of new quarks or leptons, we do not know.

After November 1984

The discoveries of November 1974 were a signal of our understanding that there was another level of structure in matter, the quarks, and that we finally had a theory of the forces involving the strong interaction and the electroweak interaction. This understanding, called the Standard Model, has been with us since. Starting at the level of molecules, the subject of chemistry, we go down in size to atoms, then to the nucleus, then to the proton and neutron, and finally the new level, that of quarks.

What's next? The most obvious path is to attempt to unify the Electroweak and Strong Interactions into one theory, so-called Grand Unification. We might even attempt to add in gravity and achieve Super Unification. In any case we will continue to push, trying to find a crack in the Standard Model — or better and more likely — something not understood in its framework. Perhaps it will point to another layer of substructure inside the quarks. Or perhaps it will indicate more interactions, observable at a higher mass scale. We all plan to continue probing this frontier, and a few hundred meters away we are building the machine that will carry that search with precision to the weak interaction scale.

The original November revolutionaries, Burt Richter and Sam Ting, chat during the symposium.