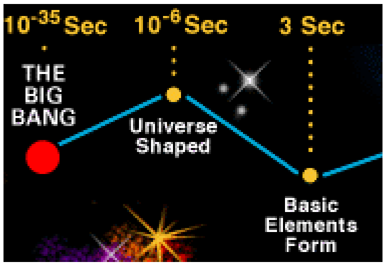
Confinement and the Search for Gluonic Excitations

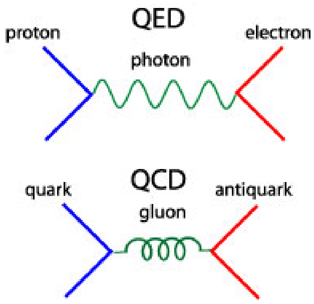


Sometime between the first picosecond (10^{-12} second) and the first microsecond (10^{-6} second) after the birth of our universe a remarkable thing happened –quarks and anti-quarks, that up to then were flying around in a wild frenzy, started to come together to form the building blocks of matter as we now know it. But how they grouped together was not random – only certain combinations apparently worked. For example, three quarks could bind to form protons or neutrons and other three-quark combinations collectively known as baryons. And quarks and anti-quarks formed pions and kaons and other similar combinations collectively known as mesons. Combinations like quark–quark or quark – quark–anti-quark, for example, do not exist. By the time that the universe had reached the mature age of 3 minutes, all of the quark matter had become tightly locked up inside the protons and neutrons, and all of the low mass nuclei that form our universise had been created.

The rules that determined how quarks and anti-quarks coalesced during the Big Bang are assumed to the same as the rules that apply today. During the last 70 years hundreds of mesons and baryons were discovered, first in the interactions of cosmic rays in our atmosphere, and later using beams from accelerators. However, with few possible exceptions, all of these are combinations of three quarks, or a quark and an anti-quark – only these combinations. But equally or even more remarkable is that once the quarks come together in these limited combinations – they are forever confined and can never again exist as free particles. The theory that we now have in hand to describe how quarks interact with each other incorporates these two facts – the peculiar combinations and the lack of free quarks – as fundamental ingredients of the theory.

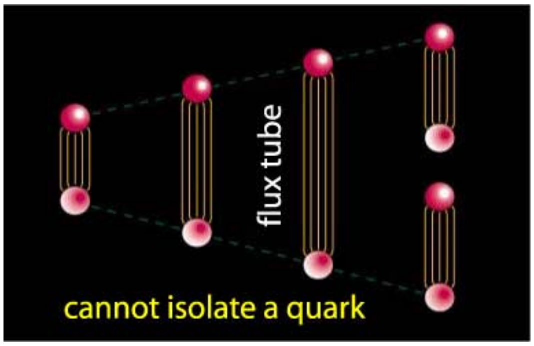
That theory is called quantum chromodynamics or QCD. It is modeled closely after the theory that explains how electrically charged particles interact and how atoms are formed – quantum electrodynamics or QED. QED brings together electricity, magnetism, quantum mechanics and special relativity and its formulation culminated in a Nobel Prize shared by American physicists Richard Feynman and Julian Schwinger and Japanese physicist Sin-Itiro Tomonaga. QED stands as a jewel among theories explaining the detailed spectrum of the simplest atom and the operation of lasers. Within this theory charged particles, like protons and electrons, interact by exchanging photons. Charged particles can emit or absorb photons and this gives rise to the force between them. But the photons do not carry electric charge and so they cannot bind to form atoms of light, as do protons and electrons do to form atoms.

QCD has many similarities to QED and the theorists who formulated it were guided by results of experiments during the 60's through 70's winning Nobel Prizes for both experimentalists and theorists alike. QCD and QED do differ in several significant ways. First of all, quarks carry more than one kind of charge. In fact they carry three kinds of charge called color charge – red, green and blue. This has nothing to do with the colors we are familiar with but it is only a naming scheme. Each of these color charges can be positive or negative (quark or anti-quark). QCD requires that combinations of quarks that can exist in nature are colorless – and the simplest combinations satisfying this are three quarks (each of different color) or quark and anti-quark (color and anti-color).



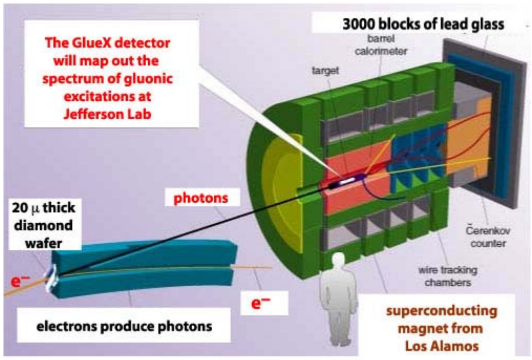
Just as photons are exchanged between electrically charged particles, gluons are exchanged between quarks and anti-quarks to explain how quarks interact. But unlike photons that are electrically neutral, gluons carry color charge. That means that it should be possible for gluons to interact with each other to form matter containing only gluons with no quarks. All that is required is that the combinations are net colorless. Combinations of two or three gluons will do the trick and such states are called *glueballs*. We have possible experimental evidence of these states but our theoretical understanding of the data is confusing. They should look like normal mesons with similar properties called quantum numbers. And therein lies the problem – they cannot be distinguished from normal mesons very easily. Other new mesons should also be possible and these would involve combinations of quarks and gluons called *hybrid* mesons. There are specific combinations that would lead to mesons with quantum numbers that are not allowed for simple quark-anti-quark combinations and these are called *exotic hybrid* mesons (*exotic* because their quantum numbers are unusual and *hybrid* because both quark and gluon properties determine the character of these mesons). Taken as group, glueballs and hybrid mesons are known as *gluonic excitations*.

Because gluons can interact with each other we have another insightful and equivalent picture of hybrid mesons – the gluons exchanged between a quark and anti-quark interact with each other to form relativistic strings or *flux tubes*. In a normal meson these flux tubes are static and this leads to normal mesons. But the flux tubes can be plucked and when it does it vibrates leading to a new family of mesons parallel to normal mesons. The quantum numbers of the plucked flux tube combine with those of the quarks to lead to normal or exotic quantum number combinations. These flux tubes lead to a force between the quarks that is large (about 16 tons!) and stays constant as the distance of the quarks increases. In contrast, the electrical force decreases as the inverse square of the distance between charged particles. If one tries to separate a quark from its partners by striking one of the quarks, for example, the energy in the quark and anti-quark system quickly grows as the distance grows and quark and anti-quark pairs spontaneously form, combining with the original quarks so that in the end all we have are mesons and/or baryons again – no free quarks. Confinement is thus explained – at least qualitatively.



Since the details of confinement are tied to the gluonic string or flux tube between the quarks, physicists concentrate on studying those particles whose character is determined by the excitation of the flux tube. This is a theoretical and an experimental challenge.

The mathematical techniques that have been used so successfully in QED work in QCD when the quarks are close together and their binding is small. Experiment and theory agree well. But at larger quark separations, corresponding to the diameter of a proton, these mathematical methods do not work and theorists resort to a technique called lattice gauge QCD. The theory is solved exactly in a discretized space-time world but requiring massive computational power. Multi-teraflop computers are needed to allow theorists to do the calculations needed to predict a detailed spectrum of exotic hybrid mesons. But the final arbiter in determining which model of confinement is correct is experiment. So in parallel experimenters are using recent developments in technology to carry out experiments that will map out the spectrum of this new type of matter with a focus on those hybrids that are distinctly different from normal mesons. They are the "smoking gun" unambiguous evidence of gluonic excitations. Some evidence that these states exist is in hand. But using beams of photons instead of π mesons (from which we have most of our data on the meson spectrum) are expected to be a rich source of exotic hybrid mesons. The photons are made by passing beams of electrons through a thin wafer of diamond crystal. Some of the electrons radiate photons passing through the diamond and these photons have a polarization (like polarized light from some sunglasses) that greatly facilitates the quantum number determination of the produced mesons whose decay products are measured by a complex detector. The technology of producing the requisite photon beam (electron beam characteristics and sufficiently thin diamond wafers several microns thick) are only now in place. And the computational hardware and software needed to analyze the petabyte-level data sets to uncover this new form of matter are only now powerful enough to make these investigations possible.



So because of the recent advances in theory, experiment and computational resources we are at last ready to answer a fundamental question: what is our quantitative understanding of the confinement. The multi-teraflop era of computation is at hand. Simulations are an important tool in all areas of science and engineering. The lattice gauge simulations will need experimental verification and the timing could not be better. Experimental results should be available soon after the detailed theoretical predictions from lattice gauge simulations are completed.

An article in an August 2000 issue of the New York Times listed the confinement question among the ten fundamental questions in physics to ponder for the 'next millennium or two.' And when we have that answer we will be on our way to an understanding of QCD at a level comparable to how we now understand QED. In many ways QCD is a far richer theory than QED. So the prospects for what that will lead to are really exciting. And we'll also have the answer to how matter – as we know it – was born soon after the creation of our universe.