Pauli's exclusion principle, Color Charge of Quarks, Asymptotic freedom and Confinement

In the earlier article "Bosons, Fermions and Pauli's exclusion principle," I explained that two or more identical fermions cannot occupy the same state. In this article, I will explain how this observation led to the introduction of color charge for quarks, and then go on to explain the peculiar properties of the force between quarks called the "strong force," which is one of the four elementary forces in our nature.

Many new particles, collectively known as "Hadrons," were discovered in the middle of 20th century. This puzzled physicists, as they did not know why there should be so many kinds of particles, and how they should interpret and relate the properties of these new particles. Some even boldly claimed that all these newly discovered particles are on equal footing. i.e. no one is more elementary than any other, nor are any composite. This idea is called "nuclear democracy."

However, this idea turned out to be wrong, as the correct solution came in 1964, when Gell-Mann proposed the "quark model," for which he later got the Nobel Prize. He showed that various properties of different hadrons can be explained if we assume that there are three different kinds or "flavors" of quarks known as "up quark," "down quark" and "strange quark," At the time, only these first three were known; three more were discovered later. Hadrons are made out of these quarks. For example, a proton, a kind of hadron, is made out of two "up quarks" and one "down quark," while a neutron, another kind of hadron, is made out of one "up quark" and two "down quarks."

Hadrons can even be composed of three of the same quarks. For example, Δ^{++} is composed of three up quarks, Δ^{-} is composed of three down quarks, and Ω^{-} is composed of three strange quarks. However, this led to a paradox, since quarks are fermions and two or more same fermions cannot occupy the same state because of Pauli's exclusion principle.

In 1965, to solve the paradox, Han and Nambu proposed that there are three different kinds of up quark despite having the same mass, three different kinds of down quark despite having the same mass, and three different kinds of strange quark despite having the same mass. In this way particles made of three of the same "flavor" of quark like Δ^{++} would be made out of three different kinds of that flavor of quark, thereby avoiding Pauli's exclusion principle. The three quarks in Δ^{++} are no longer the same, so Pauli's exclusion principle no longer applies. However, Han and Nambu's ideas of how the three different kinds of the same flavor of quark differ from one another was not entirely correct. Even though they assigned different charges (i.e. mathematically meaningful numbers labeling particles) to the different quarks, but these charges were not correct.

In 1973, Gell-Mann and Fritzsch corrected Han and Nambu's model: with the realization that each quark carries one of the three color charges: "red," "green," "blue." For example, Δ^{++} is made out of one red up quark, one green up quark and one blue up quark. Please note that the nomenclature "red," "green," and "blue" has nothing to do with the real colors observed by human eyes.

It may be a little bit hard to understand what it means that quarks carry color charges. Therefore, I want to introduce a simple analogy to the idea of electric charge, such as positive charge of protons and negative charge of electrons. The color charge behaves similarly. The only difference is the number of possible charges a particle can carry; a quark can carry any of three different color charges, while particles observing electric force can carry only two kinds of electric charge: positive and negative. (Strictly speaking, anti-quark can also carry "anti-red," "anti-green," and "anti-blue" color charge, but I will not discuss such complicated issues.) Quarks carrying color charges observe strong force. The dynamics of quarks with respect to the strong force is called "quantum chromodynamics" or "QCD." The word "chromo" comes from an ancient Greek word $\xi\rho\tilde{\omega}\mu\alpha$ meaning "color."

This analogy goes further. Just as a positively charged object and a negatively charged object attract each other, a "red" quark, a "green" quark, a "blue" quark attract one another. Moreover, negatively-charged objects such as electrons and positively-charged objects such as nuclei combine to form electrically neutral objects such as atoms. Similarly, a "red" quark, a "green" quark and a "blue" quark can combine to form a colorless hadron.

Actually, it is known that we cannot observe color directly. All hadrons are colorless. Physicists calculated the properties of hadrons assuming that each quark has a color charge, and they compared with experiments and found agreement. That's how we know that quarks carry color charge.

You may argue that if we separate out a quark from a hadron, we ought to be able to observe color directly. This is not the case since a quark cannot be isolated from a hadron. This is called "confinement." The rough idea behind this phenomenon is the following. Unlike the electric force or gravitational force which decrease and becomes zero as the range of the force increases, the force between quarks increases and eventually becomes a non-zero constant as they get farther apart. It's similar to an elongated rubber band. It gets harder to stretch as you stretch it farther. As it requires infinite energy to completely isolate a quark to the point at infinity, a quark can never be isolated.

This kind of behavior in which the force between quarks is very small when they are close together and increases as they get farther apart is called "asymptotic freedom" for which the Nobel Prize was awarded in 2004. Here, freedom refers to the fact that quarks are "free" when they are close together as the force between them is small.

Summary

- Hadrons are made out of quarks.

- There are six flavors of quarks: up quark, down quark, strange quark, and three others.
- Quarks carry color charges: red, green, blue.
- Introduction of color charges solved the paradox how three quarks of same flavor can form a hadron despite Pauli's exclusion principle.