The quark confinement: Life sentence of fundamental constituents of nature

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Abstract

The particle physics is a study of the properties and interactions of subatomic particles. Here we discuss the basics of one of the most crucial phenomena in particle physics, namely, The quark confinement. Subsequently, we describe The Bag Model of the quark confinement, which makes a phenomenology of the confinement easy to understand.

1 Introduction

The idea of quarks was put forward by Murray Gell-Mann and George Zweig in the year 1964 [1]. Later, experiments established the quarks as real physical, fundamental objects. There are six different types of the quark, namely, Up, Down, Top, Bottom, Charm and Strange. They all have an electric charge. Down, Bottom and Strange quarks have an identical charge of $-\frac{1}{3}e$; whereas Top, Up and Charm quarks have an identical charge of $\frac{2}{3}e$. All of them are massive with the top quark being the heaviest and the up quark being the lightest. Up and Down quarks are the only stable quarks. This is the reason why the ordinary matter, we see around us, is made up of them. The rest are created in high energy collisions only and quickly decay into these quarks. Each quark has its antiparticle called antiquark. A subatomic particle made of quarks is commonly known as 'Hadron'. There are two types of the hadron, namely, Meson and Baryon. Meson is composed of the quark and the antiquark of different types e.g. Pion$^+$ is composed of the up and the anti-down quark pair. Baryon is composed of three quarks e.g. Neutron is composed of two down quarks and one up quark. Having given a brief introduction about the quarks and the recipe to understand the confinement, we now proceed to the main subject of this article.

2 The quark confinement

Experimental developments over many years have confirmed the non-existence of free quarks unlike other fundamental particles such as the electron and the neutrino. What is observed instead in experiments is jets of hadrons. For example, when protons (a known member of the baryon family) or nuclei of heavy atoms such as lead are smashed in particle colliders like large hadron collider, products of collisions are jets of mesons and baryons. One such collision is shown below

$$proton + proton \rightarrow proton + neutron + pion^+$$

These experiments have unearthed the truth, which is against our day-to-day experience in a following sense. When we break something assembled, it shatters into more basic objects which make that thing and not into other similar entities. For example, when a building is blasted, it collapses into debris of cement concrete, bricks and other materials which made it and not into other different types of buildings. However, what happens after collision of protons or nuclei is exactly opposite. Parent hadrons are not broken into quarks but get converted into different daughter hadrons after collisions. Thus, the quarks by default clump together to form hadrons. So, the quarks are forever trapped inside hadrons ('life sentence'), a phenomenon known as the confinement.

The physics of the confinement phenomenon is 'the asymptotic freedom', a peculiar property of the strong force through which quarks interact. Naively, the asymptotic freedom means that the quarks do not interact with one another when they are very close and as the separation increases, strength of interaction keeps growing. Therefore, quarks tend to be close together. Again, this property contradicts a familiar classical physics. When two charges or masses are brought closer to each other, the electromagnetic or the gravitational force between them increases as $\frac{1}{r^2}$, inverse square of the distance between them, but the strong nuclear force has an opposite behavior. The phenomenology of the confinement physics can be easily understood by a simple model called "The Bag Model".

3 The Bag Model

The Bag Model was developed in 1974 by a group of physicists at the Massachusetts Institute of Technology in Cambridge (USA) [2] and soon it became popular in particle physics community. In this

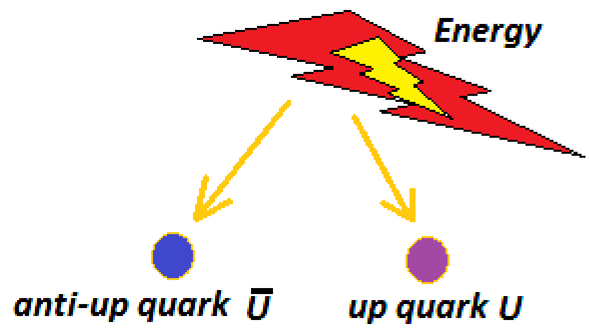

Figure 1: Example: Energy being converted into up-antiup quark pair

model, mesons are considered as elastic bags containing quark-antiquark pair and baryons are considered as elastic bags containing three quarks. When any elastic material undergoes deformation due to external force, it tries to resist the deformation. The same is true for these imaginary elastic bags but they are little weird since when the original bag is broken, new bags are formed out of it automatically.

Imagine an elastic bag as shown in fig. 2 containing quarks which represents a baryon. When a bag is unstretched, quarks can move freely in it. As soon as you try to pull a quark apart, the bag stretches and resists. More you stretch, more the energy required to stretch it even further. In other words, potential energy of two quarks is proportional to distance between them, $V(r) \propto r$. Now, the energy can be converted into equivalent mass and vice-versa as per Einstein's famous mass energy equivalence formula, $E = mc^2$. The converted mass has to be in the form of pairs of particle and its antiparticle so that the fundamental charge conservation law is conserved. A pictorial representation of one such process is given in fig. 1. At some point while stretching, it is more energetically favorable for a new quark-antiquark pair to spontaneously appear from a given energy, than to allow the bag to extend further. So at this point, the bag does not stretch further instead new quark-antiquark pairs appear from all the energy given so far for stretching the bag. These pairs destroy the original bag and again clump together in new bags, thus forming mesons and baryons. The whole process is shown pictorially in fig. 2. A collision of particles in colliders can be imagined as this process. When bags (hadrons) collide, they undergo deformation; at the energy where the pair-production is more favorable than further deformation, original bags are broken and different new bags (mesons and baryons) are created, which move away giving rise to jets. So in this way, The Bag Model correctly dummies hadrons and what might be happening at the time of collisions of hadrons so that we don't get to see individual quarks.

4 Conclusion

We explained the quark confinement and the physics responsible for it, and discussed how and why this phenomenon is drastically different from our real world experience using an example. Then we described The Bag Model which helps understand the confinement phenomenon easily.

References

[1] M. Gell-Mann, *phys. Lett.* **8**, 214-215 (1964) George Zweig, Unpublished

[2] A. Chodos, R. L. Jaffe, K. Johnson and C. B. Thorn, *Phys. Rev. D* **10**, 8 (1974)

Suggested Readings:

- David J. Griffiths, *Introduction to Elementary Particles*, John Wiley sons, New York, pp.1-78, 2004

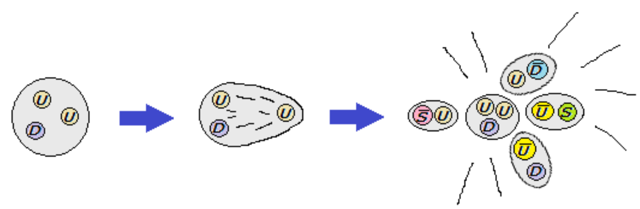

Figure 2: Bag model of quark confinement