

Quarks and the Strong Force Summary/Review

Spring 2009 Compton Lecture Series:
From Quantum Mechanics to the String
Nelia Mann

- Mesons and Baryons can be fit into patterns according to quark number, spin, mass, and charge.
 - Large numbers of new particles were discovered between 1947 and 1964 which behave like heavy versions of protons, neutrons, and pions
 - These particles can be separated into two groups: one with non-zero quark number and the other with zero quark number
 - The non-zero quark number particles are all either spin $1/2$ or spin $3/2$. The zero quark number particles are all either spin 0 or spin 1
 - Within these four groups, organizing by mass and charge leads to hexagon and triangle patterns of particles
- Baryons are made up of three quarks, mesons are made up of a quark and an anti-quark
 - The quarks in these patterns have come in three flavors: up, down, and strange. The particles with more strange quarks in them have higher masses.
 - The baryon patterns have equivalent patterns of anti-baryons (made up each of three anti-quarks.) The meson patterns contain both in a particle/anti-particle pair.
 - There are three more flavors of quarks: 6 in total: down, up, strange, charm, top, bottom. These can be split into pairs, one of which has charge $+2/3$ and the other has charge $-1/3$. Each of these pairs goes with an electron (or a heavier version: muon or tau) and a neutrino. These sets of four particles are called generations.
- Quarks have a quantity called “color”, which is to the strong force what charge is to the electromagnetic force
 - Color is necessary to reconcile certain baryons’ quark content with the Pauli exclusion principle, which states that two fermions cannot exist in the same state as each other
 - In addition, it is the “charge” of the strong force, which is mediated by gluons
 - Gluons are massless, spin 1 particles (like photons.) Unlike photons, they come in 8 varieties, each of which carries a unit of color and a unit of anti-color. Because of this, they interact directly with each other.
- Quantum shielding causes the strong force to grow with distance , holding colored objects together as if by a spring
 - Unlike with the electromagnetic force, where the quantum effects of virtual charged particle decrease the effect of the force, in this case (because the gluons themselves carry charge) the quantum effects increase the effect of the force
 - Though classically the force decreases with distance $\propto \frac{1}{r^2}$, with the quantum corrections the force *increases* with distance $\propto r$. This behavior mimics that of objects connected by springs.
 - It requires an infinite amount of energy to separate two colored objects. If you start to put enough energy into (for example) a meson, to try to pull it apart, once you have put enough in to produce another quark/anti-quark pair, this is what happens instead. You wind up with two colorless mesons which separate easily.

- In a particle experiment, if you put enough energy into a meson or a baryon to start to pull the quarks apart, what results is messier: “jets” of mesons and baryons are generated.
- The nuclear force and pion exchange is a residual effect from the color structure of baryons which have no net color
 - Protons and neutrons carry no net color, but they do have internal color structure. Like atoms or molecules which are electrically neutral but which attract each other slightly because of their internal electrical structure, the protons and neutrons stick together. The force decreases rapidly with distance because as you get further away from the proton or neutron, the internal structure becomes less important and only the colorlessness remains.
 - Pion exchange is the dominant effect at ranges where only colorless objects can exist: the protons and neutrons cannot exchange colored gluons at those ranges.