

# String and the Strong Force Summary/Review

Lecture 9: Spring 2009 Compton Lecture Series:

From Quantum Mechanics to the String

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- Mesons have behaviors that might be explained if they are really small open strings.
  - The eight-fold way of meson nonets led to the discovery of quarks as an explanation for this pattern.
  - Mesons also fall into families of similar particles where increasing mass is correlated with increasing spin. Graphing spin against mass squared leads to a line of particles called a “Regge trajectory.”
  - This might be explained by string theory because if mesons are really open strings then the more wiggles an open string has, the greater it’s mass is *and* the greater it’s spin. In fact, string theory predicts just such a linear relationship.
  - In QCD, mesons are formed as combinations of quarks and anti-quarks, with a strong field stretching between them that doesn’t spread out (and thus doesn’t weaken with distance). This looks a little like a string.
  - If you try to pull the meson apart, in the QCD picture you end up producing another quark/anti-quark pair, which results in having two mesons. This could equally be explained if the mesons are really strings: if you pull apart a string, what you get is two smaller strings.
  - Proton and neutron interactions are explained by the exchanges of pions, along with other mesons. If particles can interact by exchanging one meson, they can generally interact by exchanging any meson on that Regge trajectory. To get the full effect of these interactions, you must add up all these possible exchanges. This ends up giving the same result as the exchange of an open string. The exchanged open string is never measured and might have any number of wiggles on it.
  - Closed strings would then describe glueballs: bound states of gluons which together are colorless. Glueballs have never been experimentally confirmed (it can be difficult to tell the difference between a glueball and some highly unstable meson) but numerical calculations of QCD show their existence and predict their masses. Baryons are harder to imagine as strings; usually they are pictured as some complicated combination of open strings.
- Quarks and gluons interacting also begins to look a little like string theory
  - In quantum electrodynamics (QED), two electrons interacting is well described by the exchange of one photon. They might also exchange two photons, but this process is much less likely. Even more complicated interactions are even less likely, allowing us to organize what occurs by which interactions happen the most often and then in order of decreasing likelihood.
  - By contrast, in the strong force, quantum chromodynamics (QCD) the emission of a gluon by a quark, or the emission of a gluon by a gluon, is very likely. The exchange of one gluon by a pair of quarks is actually less likely to occur than the exchange of many, in some complicated array. If you try to draw the interaction of a quark and an anti-quark, you wind up with a complicated “netting” of quark and gluon interactions, which is extremely dense. It begins to look a little like an open string, traveling through time, with the netting approximating the sheet the string traces out.
  - You can redraw this interaction to keep track of the flow of color. Since quarks carry one unit of color and gluons carry one unit of color and one unit of anti-color, quarks are represented by a single line with an arrow showing where the color goes, while gluons are a pair of parallel lines with arrows in opposite directions. The incoming and outgoing quarks will have some definite color, but the netting has closed loops in the middle which can each be any color, and still end up with a valid interaction.

- In QCD there are 3 colors, but you can imagine a system with some arbitrary number  $N$  of colors. Since every time there is a closed loop, there are  $N$  possibilities for what color it might be, the interaction becomes  $N$  times as likely for every closed loop. If there is a quark loop in the diagram, then it is  $1/N$  times as likely as the same diagram with the quark loop replaced by a gluon loop.
- If you replace the netting by the sheet of a string, then a quark loop becomes a hole in the sheet, where the string splits into two strings and then rejoins. The statement that this is less likely than the diagram where the string doesn't split means that the string's path is more likely when there are less *string interactions* (just like the QED diagrams with fewer photon interactions were more likely.)
- It's possible that the strong force might be equally well described by QCD and by strings.
  - A  $3 + 1$  dimensional QCD-like theory can also be described by a  $4 + 1$  dimensional gravitational theory
  - String theory with 5 compact dimensions would be a  $4+1$  dimensional gravitational theory. In this case, the QCD-like theory would live on the boundary of the  $4+1$  dimensional space.
  - Depending on the shapes of the  $4+1$  dimensional space and the 5-dimensional compact space, you get a different type of QCD-like theory.
  - If the 5 compact dimensions form a 5-sphere and the  $4+1$  dimensions form what is called an “anti-de-Sitter” space (which is similar to a 5-sphere but with negative curvature) (this is a choice with a large amount of symmetry) then the QCD-like theory on the boundary is very simple. It is supersymmetric (meaning for every fermion there is a boson of equal mass and playing the same role in the theory), it has no quarks (just gluons and a kind of fermionic gluon) and it doesn't confine color, so isolated objects can have color.
  - This is pretty different from QCD, but it is extremely simple to work with, by comparison. We are close to having a mathematical proof for the equivalence of the QCD-like theory to the string theory.
  - For QCD itself, we don't know exactly what the shape of the 5 compact and  $4+1$  non compact dimensions should be. We only know that the 5 compact dimensions should make something more complicated than a 5-sphere (so there isn't as much symmetry) and the  $4+1$  non-compact dimensions should make something more complicated than the AdS shape (which is associated to the fact that the particle theory doesn't confine colors.)