The Origin and Nature of Quark Confinement: Discovering and Studying the Exotic Mesons

In the early 1970s, evidence that the masses of strongly interacting particles increased without limit as their internal angular momentum increased led the theorist Yoichiro Nambu [Na70] to propose that the quarks inside these particles are "tied together" by strings. Numerical simulations of QCD ("lattice QCD") have demonstrated [Ba00] that Nambu's conjecture was essentially correct: in chromodynamics, a stringlike chromoelectric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see Figs. 1 and 2). The phenomenon of confinement is the most novel and spectacular prediction of QCD – unlike anything seen before. It is also the basic feature of QCD that drives all of nuclear physics, from the mass of the proton and other nuclear building blocks to the NN interaction.

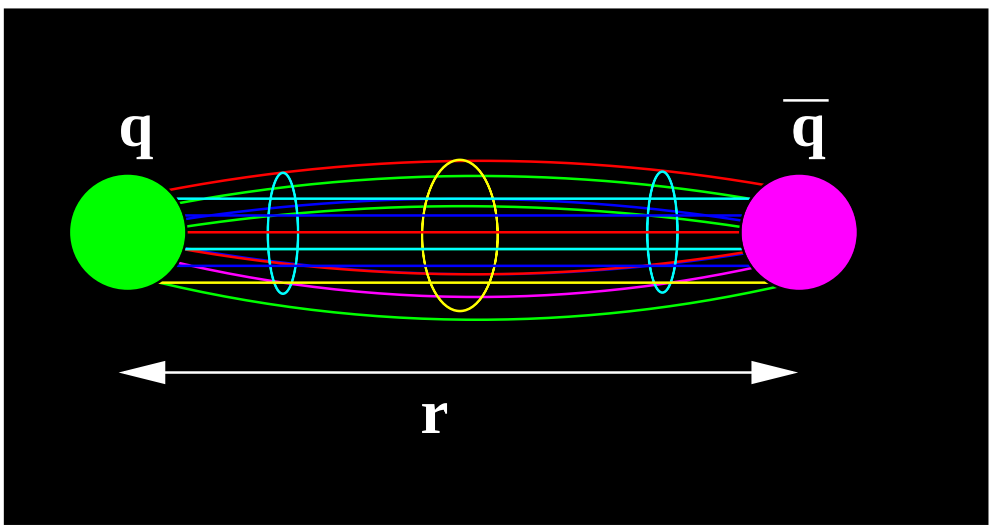

Figure 1: In QCD a confining flux tube forms between distant static charges. The Hall D program is designed to verify this fundamental new feature of chromodynamics.

The ideal experimental test of this new feature of QCD would be to study the flux tube directly by anchoring a quark and antiquark several fermis apart and examining the flux tube that forms between them. In such ideal circumstances one of the fingerprints of the gluonic flux tube would be its model-independent spectrum [Lu81] (see Fig. 3): its required two degenerate first excited states are the two longest-wavelength vibrational modes of this system, while their excitation energy is required to be π/r since both the mass and the tension of this "relativistic string" arise from the energy stored in its color force fields. Such a direct examination of the flux tube is, of course, not possible experimentally, but such a picture is indicated by lattice calculations, at least at large separations [Ju02]. In real life we have to be content with systems in which the quarks move. Fortunately, we know both from general principles [Is85] and from lattice QCD calculations [Ju99] that an approximation to the dynamics of the full system that ignores the impact of these two forms of motion on each other works quite well – at least down to quark masses of the order of 1 GeV.

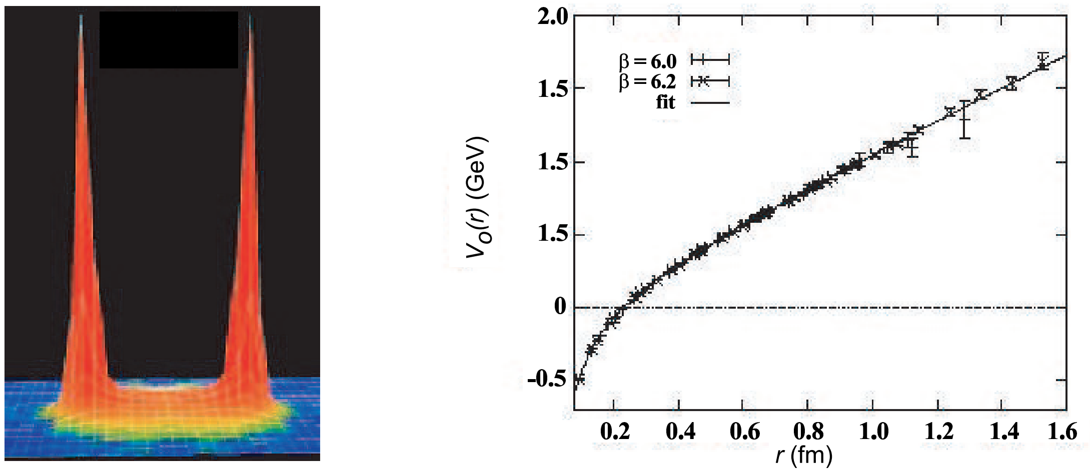

Figure 2: Lattice QCD has confirmed the existence of flux tubes between distant static charges for heavy quarks. In addition to the intense color fields in the immediate vicinity of each quark, one can see the formation [Ba00] along the line connecting the two quarks of a flux tube of constant thickness, leading to the linearly rising potential seen on the right [Ba97].

To extend this firm understanding to yet lighter quarks, models are required [Is85], but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV, a new form of hadronic matter must exist in which the gluonic degree of freedom of a quark-antiquark system is excited. The smoking gun characteristic of these new states is that the vibrational quantum numbers of the gluonic "string", when added to those of the quarks, can under certain circumstances produce a total angular momentum J, a total parity P, and a total charge conjugation symmetry C not allowed for ordinary $q\bar{q}$ states. These unusual J^{PC} combinations (such as 0^{+-}, 1^{-+}, and 2^{+-}) are called exotic, and the states are referred to as exotic hybrid mesons [Ba77]. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations, require that these states have masses around 2 GeV; furthermore, they demonstrate that the levels and their orderings will provide experimental information on the mechanism that produces the flux tube.

On the experimental front, tantalizing evidence has appeared in recent years for both exotic hybrids and gluonic excitations with no quarks (glueballs). For the last two years a group of 90 physicists from 26 institutions in seven countries has been working on the design of the definitive experiment to map out the spectrum of these new states required by the confinement mechanism of QCD. Photon beams are expected to be particularly favorable for the production of the exotic hybrids [Is85]. The reason is that the photon sometimes behaves as a "virtual vector meson" with total quark spin $S = 1$. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic J^{PC} are possible. In contrast, when

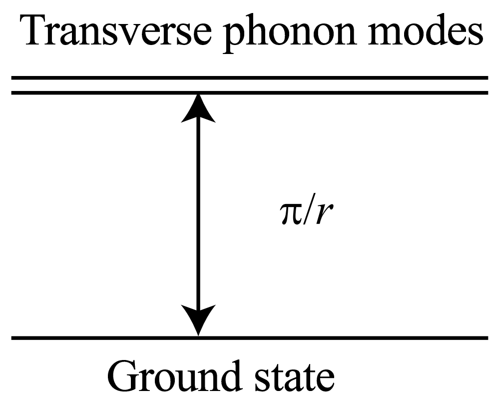

Figure 3: Model-independent spectrum of the glue (flux tube) of Fig. 1.

the spins are antiparallel ($S = 0$), as in pion or kaon probes, the exotic combinations are not generated. (In the approximation that flux tube and quark dynamics separate, hybrid production would occur by pure flux tube excitation, and these selection rules would be strictly true. In practice, these two degrees of freedom interact with one another to produce corrections to the rules.) To date, most meson spectroscopy has been done with incident pion, kaon, or proton probes, so it is not surprising that the experimental evidence to date for flux tube excitation is tentative.

In contrast to hadron beams, high-flux photon beams of sufficient quality and energy to perform meson spectroscopy studies have not been available, so there are virtually no data on the photoproduction of mesons with masses in the 1.5 to 3 GeV region. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found. The planned experiment will have a dramatic impact on this situation. Even if initial running is at only 10% of the planned photon fluxes of 10^8/s, the experiment will accumulate statistics during the first year of operation that will exceed the world's supply of published meson data obtained by pion production by at least a factor of 10, and the existing photon production data set by at least a factor of 1000. With the planned detector (see Fig. 4), high statistics, and linearly polarized photons, it will be possible to map out the full spectrum of the decay modes of these gluonic excitations. This experiment is described in Section 4.E; a much more complete discussion of the physics driving the experiment is given in Section 2.A.

When the spectrum and decay modes of these gluonic excitations have been mapped out experimentally, we will have made a giant step forward in understanding one of the most important phenomena discovered in the twentieth century: quark confinement.

References

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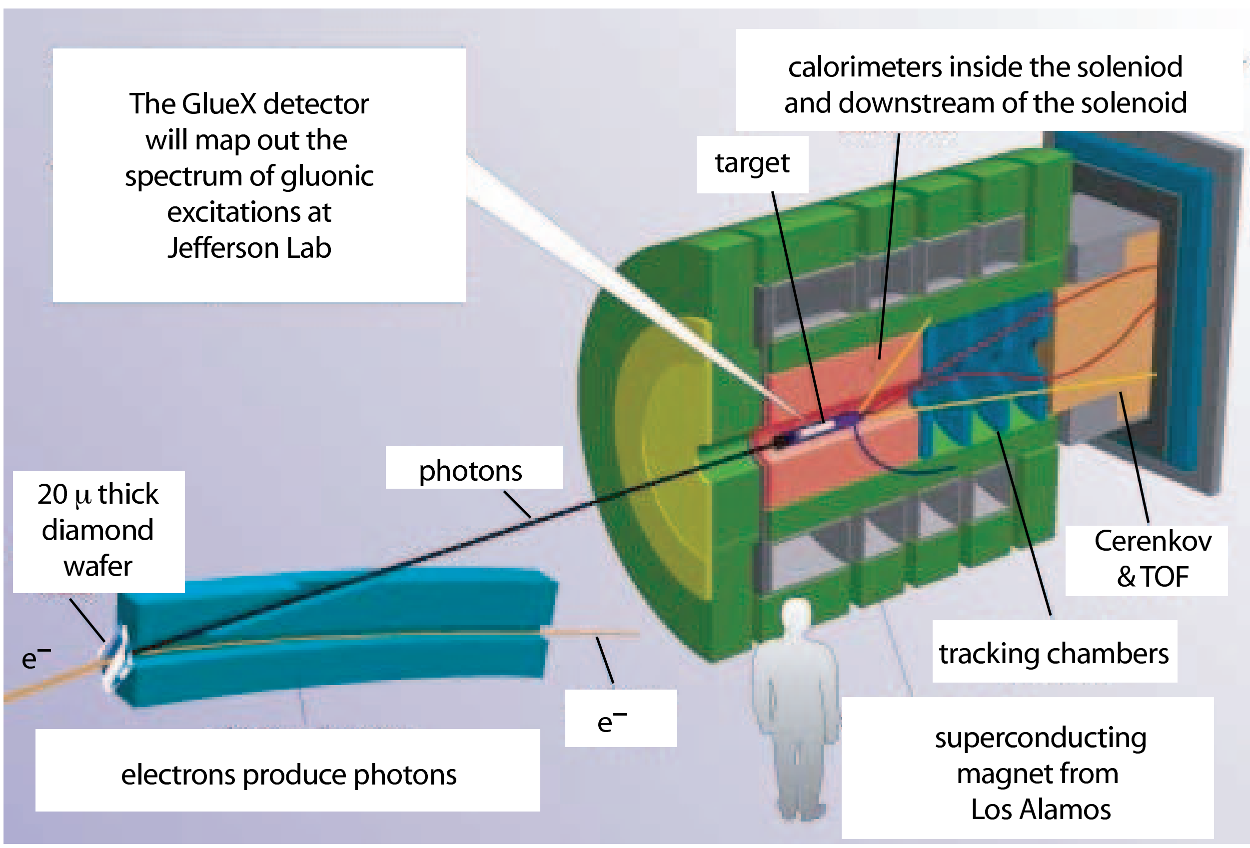

Figure 4: The conceptual design of the proposed detector to study the photoproduction of mesons in the mass region around 2 GeV.