Quark Confinement and the Hall D Project at Jefferson Lab

In the early 1970's, evidence that the masses of strongly interacting particles increased without limit as their internal angular momentum increased led the Japanese theorist Yoichiro Nambu to propose that the quarks inside of these particles are "tied" together by strings. Today the string theories which emerged from this idea are being examined as candidates for the ultimate theory of nature, while we know that the strong interactions are instead described by quantum chromodynamics (QCD), the field theory in which quarks interact through a "color" force carried by gluons. Though it is therefore not fundamentally a string theory, numerical simulations of QCD ("lattice QCD") have demonstrated that Nambu's conjecture was essentially correct: in chromodynamics, a string-like chromoelectric flux tube forms between distant static charges, leading to quark confinement and a potential energy between a quark and the other quarks to which it is tied which increases linearly with the distance between them. The phenomenon of confinement is the most novel and spectacular prediction of QCD - unlike anything seen before.

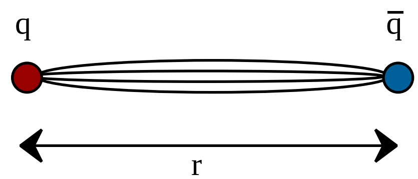


Figure 1: In QCD a confining flux tube forms between distant static charges. The Hall D program is designed to verify this fundamental new feature of chromodynamics.

The ideal experimental test of this new feature of QCD would be to directly study the flux tube of Figure 1 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 the model-independent spectrum shown in Figure 2. The two degenerate first excited states are the two longest wavelength vibrational modes of this system; π / r is their excitation energy 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.

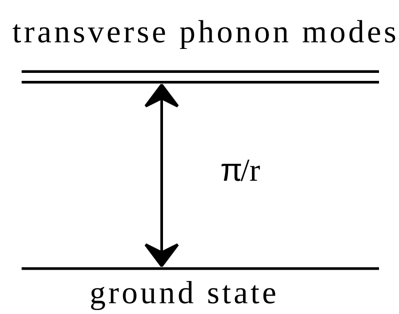


Figure 2: Model–independent spectrum of the glue (flux tube) of Figure 1.

In real life we have to be content with systems in which the quarks move. Fortunately, we know both from general principles and from lattice QCD that an approximation to the dynamics of the full system which ignores the impact of these two forms of motion on each other works quite well - at least down to the charm quark mass.

To extend the flux tube picture to yet lighter quarks, models are required, but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around $2 \text{ GeV}/c^2$, a new form of hadronic matter must exist in which the gluonic degree of freedom of mesons is excited. The smoking gun characteristic of these new states is that the vibrational quantum numbers of the string, when added to those of the quarks, can produce a total angular momentum J, a total parity (or mirror-inversion symmetry) P, and a total charge conjugation (or quark-antiquark interchange) symmetry C not allowed for ordinary $q\bar{q}$ states. These unusual J^{PC} combinations, like 0^{+-}, 1^{-+}, and 2^{+-}, are called exotic, and the states are referred to as exotic hybrid mesons.

Not only general considerations and flux tube models, but also first-principles lattice QCD calculations, require that these states are in this mass region, while also demonstrating that the levels and their orderings will provide experimental information on the mechanism which produces the flux tube. Moreover, tantalizing experimental evidence has appeared over the past several years for exotic hybrids as well as for gluonic excitations with no quarks (glueballs). For the last two years a group of 80 physicists from 25 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. This experiment is part of the planned 12 GeV Upgrade of the CEBAF complex at Jefferson Lab in Newport News, Virginia.

Figure 3 shows a conceptual design of the proposed detector to study the photoproduction of mesons in the mass region around $2 \text{ GeV}/c^2$. Photon beams are expected to be particularly

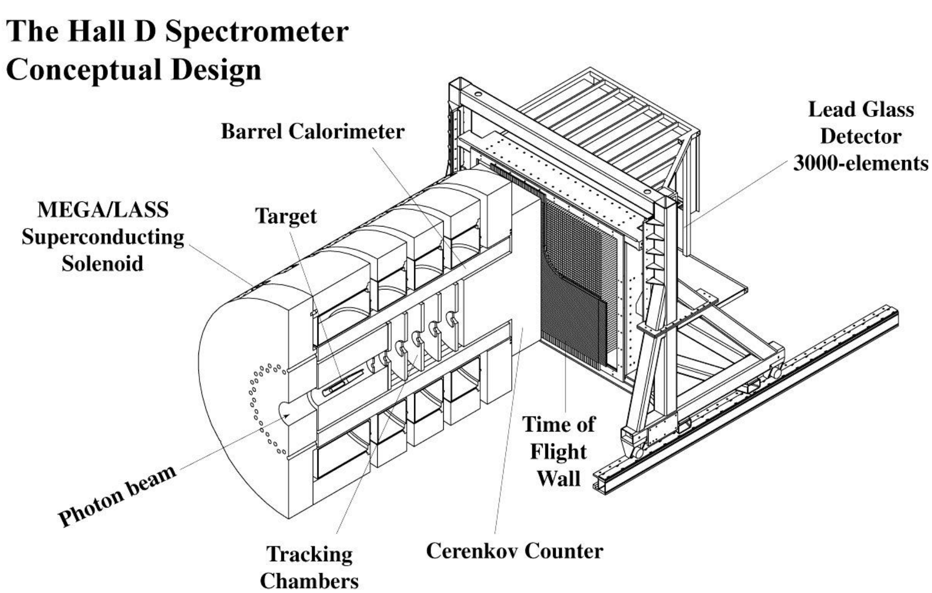


Figure 3

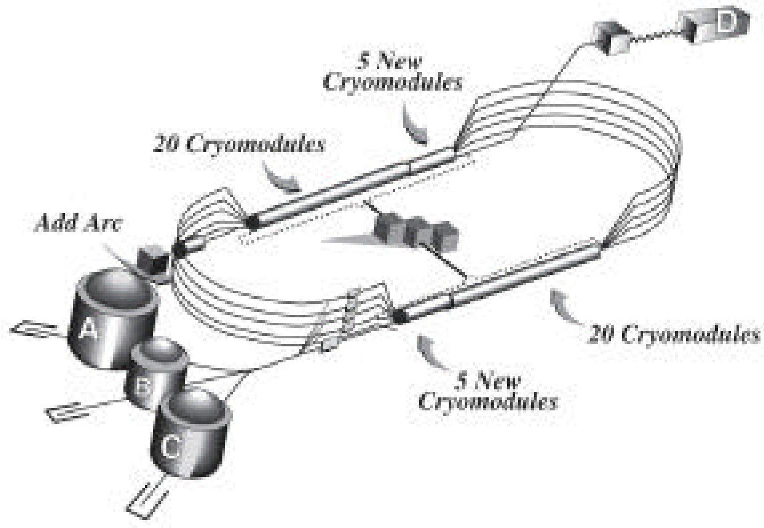
favorable for the production of the exotic hybrids. The reason: the photon sometimes behaves as a virtual vector meson (a $q\bar{q}$ state with the quark spins parallel, adding up to total quark spin S = 1). When the flux tube in this $S = 1$ system is excited to the levels shown in Figure 2, both ordinary and exotic J^{PC} are possible. In contrast, when the spins are antiparallel (S = 0), as in pion or kaon probes, the exotic combinations are not generated. To date, most meson spectroscopy has been done with incident pion, kaon or proton probes. High flux photon beams of sufficient quality and energy have not been available, so there are virtually no data on the photoproduction of mesons below 3 GeV / c^2. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found.

The Hall D detector is optimized for incident photons in the energy range from 8 to 9 GeV to access the desired meson mass range. The use of a solenoidal spectrometer allows for the measurement of charged particles with excellent efficiency and momentum determination while at the same time containing the shower of unwanted electron-positron pairs associated with the photon beam. Photons will be produced using a "coherent bremsstrahlung" technique by passing a fine electron beam from the CEBAF accelerator though a wafer-thin diamond crystal: At special settings for the orientation of the crystal, the atoms of the crystal can be made to recoil together from the radiating electron leading to an enhanced emission at particular photon energies and yielding linearly polarized photons. With the planned photon fluxes of 10^7/sec and the continuous CEBAF beam, the experiment will accumulate statistics during the first year of operation which will exceed extant data with pions by at least an order of magnitude. With this detector, high statistics, and the linear polarization information, it will be possible to map out the full spectrum of these gluonic excitations.

A committee chaired by David Cassel (Cornell) and consisting of Frank Close (Rutherford Lab), John Domingo (Jefferson Lab), William Dunwoodie (SLAC), Donald Geesaman (Argonne), David Hitlin (Caltech), Martin Olsson (Wisconsin) and Glenn Young (Oak Ridge) reviewed the project plans in December 1999. They concluded that the project is "well-suited for definitive searches for exotic states that are required according to our current understanding of QCD." They further pointed out that because of the exceptional quality of the beams at Jefferson Lab, the laboratory is uniquely suited for carrying out such studies.

In order to achieve the required photon energy and flux with coherent bremsstrahlung, an electron beam of 12 GeV is required. Figure 4 shows the current CEBAF complex with the existing three experimental Halls (A, B and C) and the planned Hall D. The addition of state of the art

Figure 4



accelerating units ("cryomodules") in existing space in the linear sections of the accelerator, along with upgrading of magnets in the arcs, will bring the electron energy up from the current maximum of 5.5 GeV to 12 GeV.

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 new phenomena discovered in the 20th century: quark confinement.

Alex Dzierba (Indiana University) and Nathan Isgur (Jefferson Lab)