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THE GLUEX PROJECT AT JEFFERSON LAB

Zisis Papandreou
Department of Physics, University of Regina, Regina, SK S4S0A2 Canada

Abstract

One of the main scientific questions that remains unanswered in subatomic physics is the nature and behaviour of the "glue" which holds the quarks together. The puzzling feature of this construction is that quarks are never found free, a phenomenon known as confinement. Since gluons carry colour charge they cause the formation of chromoelectric flux tubes, which may yield unusual objects such as glueballs or hybrids. In certain models the latter can be produced with quantum numbers not allowed in the simple quark model and these are a powerful signature for hybrid meson spectroscopy. An international experiment (GlueX) at Jefferson Lab, Virginia, is being designed to search for such exotic hybrid mesons and thus elucidate the phenomenon of confinement. GlueX is considered a "discovery" experiment; its salient features and the planned methodology of amplitude analysis will be presented.

1 Introduction

The primary goal of the GlueX/Hall-D project is the definitive and detailed mapping of the spectrum of a new family of particles called *hybrid mesons*, starting with those that carry exotic quantum numbers. Linearly polarized photons produced by electrons from an energy-doubled Jefferson Lab will be the probe used to uncover this spectrum. This experimental information is absolutely critical in achieving a quantitative understanding of the confinement mechanism in quantum chromodynamics.

The Hall-D/GlueX Collaboration was formed at a workshop held in July 1997 at Indiana University. The project has successfully passed several internal and external reviews that culminated in the Department of Energy's (DOE) award of Critical Decision Zero (CD-0, 'mission need') in 2004 and, most recently, of CD-2 ('baseline performance') in November 2007. CD-4 ('start of operations') is expected in 2015. Further details on the project can be found in references 1, 2, 3).

2 Theoretical Motivation

2.1 Overview

Strong interactions are described by quantum chromodynamics (QCD), the field theory in which quarks interact through a *color* force carried by gluons. Lattice QCD (LQCD) numerical simulations support the notion that a string-like chromoelectric flux tube forms between distant static color charges, leading to quark confinement and a potential energy between quarks that increases linearly with the distance between them. It qualitatively explains confinement: infinite energy would be needed to separate quarks to infinity. Confinement is the most novel and spectacular feature of QCD.

Figure 1 illustrates the chromodynamic energy density in the vicinity of a quark and antiquark based on a LQCD calculation 4). This calculation is for heavy quarks in the quenched approximation. The ground state potential between the quarks has a $1/r$ dependence at small distances and is linear for large distances. The energy peaks at the positions of the quarks and in the space between the quarks the energy is confined to a flux tube. Such flux tubes arise because of the self-interaction of the gluons of QCD.

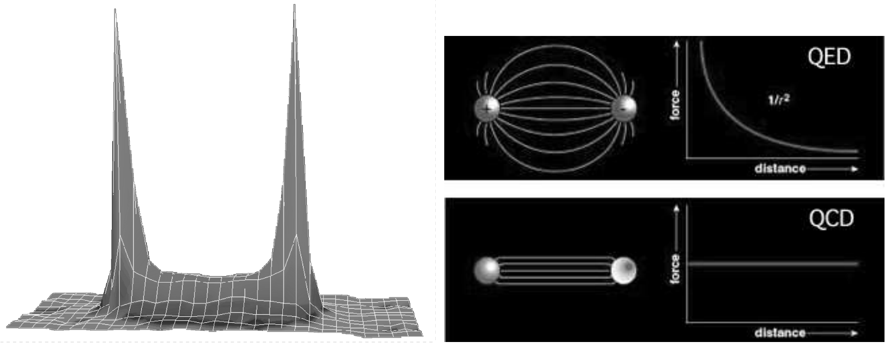

Figure 1: *Left: A LQCD calculation of the energy density in the color field between a quark and an anti-quark in a meson with a separation of 1.2 fm. Right: QED and QDC dipoles; note the difference in the field lines and in the corresponding dependence of force on quark separation.*

Although this picture must be extended to yet lighter quarks, nevertheless, the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV/c^2, a new form of hadronic matter must exist in which the gluonic degree of freedom of mesons is excited. The unique 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 P, and a total charge conjugation symmetry C not allowed for ordinary $q\bar{q}$ states. These unusual states are referred to as *exotic hybrid mesons.* The levels of these states and their orderings will provide experimental information on the mechanism which produces the flux tube.

2.2 Quark Model and QCD

QCD incorporates the experimental fact that the quarks and gluons do not exist as free particles by requiring that only color singlet combinations exist as free particles in nature. In addition to the color singlet combinations $q\bar{q}$ and qqq others are possible, such as $q\bar{q}g$ (*hybrid mesons*) and gg or ggg (*glueballs*). These new states, collectively known as *gluonic excitations*, are fascinating since this is the only case of a theory in which the gauge particle is also a constituent. The analogous states in QED, like atoms of light, cannot exist.

The early version of the quark model described the observed mesons as bound states of a quark and antiquark, where the quarks were assumed to be the u, d and s quarks. Thus mesons were grouped in families with nine members – a nonet – characterized by a given J^{PC} determined by the relative spin of the two quarks and their relative orbital angular momentum. Radial excitations are also allowed.

The rules for allowed values of J^{PC} follow from the requirements of a fermion–antifermion system: the quark spins can be parallel ($S = 1$) or antiparallel ($S = 0$) with relative orbital angular momentum (L), $\vec{J} = \vec{L} + \vec{S}$, $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. Exotic (e.g. $J^{PC} = 1^{-+}$) combinations are not allowed for $q\bar{q}$ systems. Indeed, the initial absence of such combinations gave credence to the quark model.

2.3 Gluonic Excitations

At short distances – the regime of asymptotic freedom – perturbative techniques are applicable and QCD describes high energy experimental phenomena and data both qualitatively and quantitatively. At large distance scales – the confinement regime – the situation is far different. Here we must rely on first-principles LQCD calculations or QCD-inspired models. Recent advances in algorithms and computing power now make possible LQCD predictions for masses of exotic hybrid mesons 5) and eventually their widths and decay modes.

Within the flux-tube model, conventional mesons result when the flux tube is in its ground state whereas excitations of the flux tube lead to hybrid mesons. The first excited state of the flux tube is a transverse excitation. The flux tube, or string, spins clockwise or counter-clockwise around the $q\bar{q}$ line leading to two degenerate states – degenerate since the energy should not depend on which way the flux tube is spinning. LQCD and flux tube models both indicate that the lowest excited flux tube has $J = 1$ 6, 7, 8). The linear combinations of the clockwise or counter-clockwise rotations are eigenstates of parity and charge conjugation leading to two possibilities for the excited flux tube: $J^{PC} = 1^{-+}$ or $J^{PC} = 1^{+-}$. Suppose we start with the $q\bar{q}$ in the $S = 0$ and $L = 0$ (or $J^{PC} = 0^{-+}$ – the π or K) configuration. Combining this with $J^{PC} = 1^{-+}$ or $J^{PC} = 1^{+-}$ of the excited flux tube results in hybrid mesons with $J^{PC} = 1^{++}$ or $J^{PC} = 1^{--}$. These are non-exotic quantum numbers. If, however, we start with $q\bar{q}$ in the $S = 1$ and $L = 0$ (or $J^{PC} = 1^{--}$ – the vector photon) configuration, the resulting hybrid meson can have $J^{PC} = [0, 1, 2]^{+-}$ for the flux tube with $J^{PC} = 1^{-+}$ and $J^{PC} = [0, 1, 2]^{-+}$ for the flux tube with $J^{PC} = 1^{+-}$. We note that of these six possible J^{PC} combinations, three are exotic: $J^{PC} = 0^{+-}$, $J^{PC} = 1^{-+}$ and $J^{PC} = 2^{+-}$. Figure 2 shows our current knowledge of conventional and exotic $q\bar{q}$ states.

After about two decades of experimental searches there have been reports of experimental observations of states with exotic $J^{PC} = 1^{-+}$. The conclusion from these studies is that, whereas there are tantalizing hints of gluonic excitations in both the glueball and hybrid sectors, the results are not conclusive.

3 Photon Beam

As mentioned above, the photon is expected to be particularly effective in producing hybrids with exotic J^{PC}. Figure 3 illustrates the differences between a π and a γ probe. If the scattering results in excitation of the flux tube, one expects exotic hybrid mesons to be suppressed in π-induced interactions and enhanced in photoproduction. Current phenomenology supports the notion that photons should be more effective at producing exotic hybrids 9, 10), and recent flux-tube model calculations 11, 12) suggest that the coupling between a conventional meson, a photon and a hybrid meson are not small and that we may expect copious production of hybrid mesons. The assumptions underlying such models need to be tested in a framework closer to QCD.

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. From considerations related to the production yield and boost of the exotic mesons, ability to separate meson from baryon resonances, and degree of linear polarization, the optimum photon beam energy is between 8 and 9 GeV, which translates into an electron beam energy of 12 GeV. Figure 4 shows the accelerator complex at Jefferson Lab with the existing three experimental Halls A, B and C and the planned Hall D. The addition of state-of-the-art accelerating units (*cryomodules*) in the 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 MeV to 12 MeV. New accelerator technology will yield a beam with high

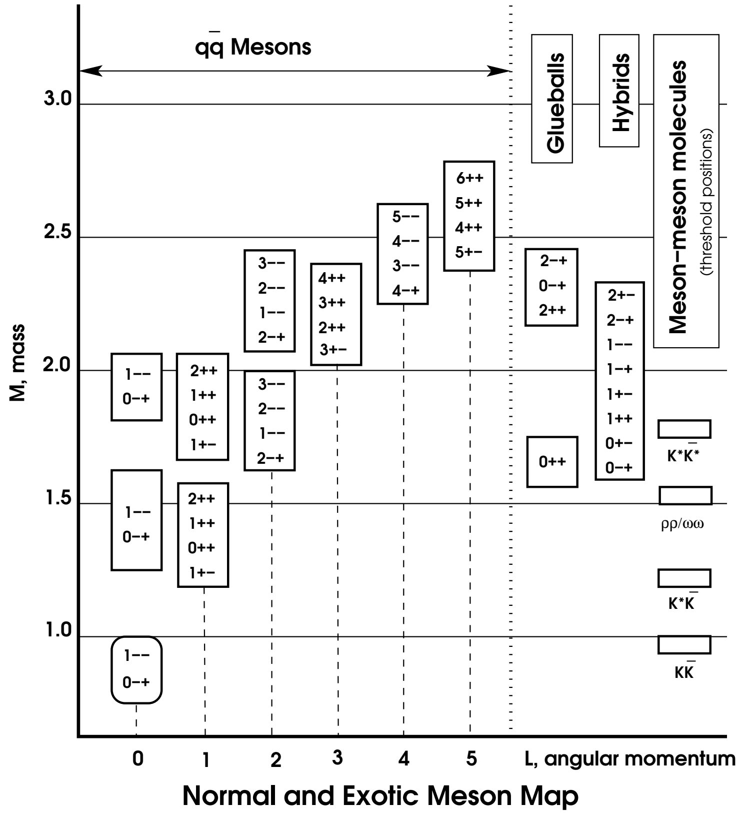

Figure 2: *A level diagram showing conventional nonets and expected masses of glueballs, hybrids, and meson-meson molecular thresholds. The vertical axis is in units of* GeV/c^2. *L refers to the angular momentum between the quarks and each box with* J^{PC} *numbers refers to a nonet of mesons. The exact association of an observed meson with a particular* $q\bar{q}$ *state within a nonet depends on a good understanding of the various decay modes of the meson as well as its mass, width and production characteristics. The range of masses of the known conventional meson nonets and their radial excitations extend from the* π *mass up to about 2.5* GeV/c^2. *The low-lying glueballs mix with conventional* $q\bar{q}$ *mesons, which complicates their identification. In contrast, hybrid mesons can possess* J^{PC} *numbers not possible for* $q\bar{q}$ *and thus have a smoking gun signature. Note also that exotic* J^{PC} *–* 0^{+-}, 1^{-+}, 2^{+-} *– occur only among the hybrids for the range of masses shown.*

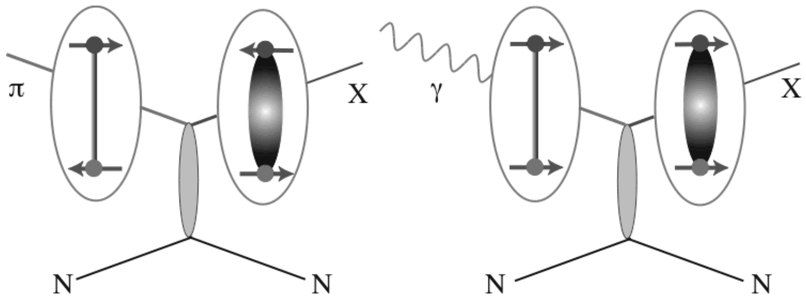

Figure 3: *Left: With a* π *probe the incoming quarks have* $L = 0$ *and* $S = 0$*. The excited flux tube from the scattering results in hybrid mesons with non-exotic quantum numbers. Right: With a photon probe the incoming quarks have* $L = 0$ *and* $S = 1$*. When the flux tube is excited, hybrid mesons with exotic quantum numbers are possible.*

flux, large duty factor, low emittance and small spot size.

The photon beam is produced by having the electron beam incident on a thin (∼20 μm) diamond wafer. The technology to produce these wafers is only now being perfected. After passing through the wafer, the electron beam is bent by a dipole magnet (the tagger magnet) into the beam dump. A small fraction, about 0.01% of the electrons, emit a photon via incoherent bremsstrahlung or coherent bremsstrahlung, the latter leading to an enhancement over the incoherent spectrum at a photon energy determined by the angle between the incident electron direction and the wafer. By exploiting the tight energy-angle correlation for the coherent photons, collimation of the photon beam can be used to enhance the fraction of photons of the coherent radiation incident on the GlueX target. This has the effect of increasing the degree of linear polarization and eliminating a large fraction of the low-energy photons that dominate the incoherent component of the spectrum. An active collimator, with a 3.5 mm hole, will be placed just upstream of the GlueX detector and about 75 m downstream of the tagger magnet. The electrons emitting the bremsstrahlung photons will be momentum analyzed using a focal plane spectrometer leading to a photon energy resolution of 0.2%. This technique allows separating the coherent from the incoherent and in the process turns the coherent spectrum with its large incoherent background into a spectrum at the target that is

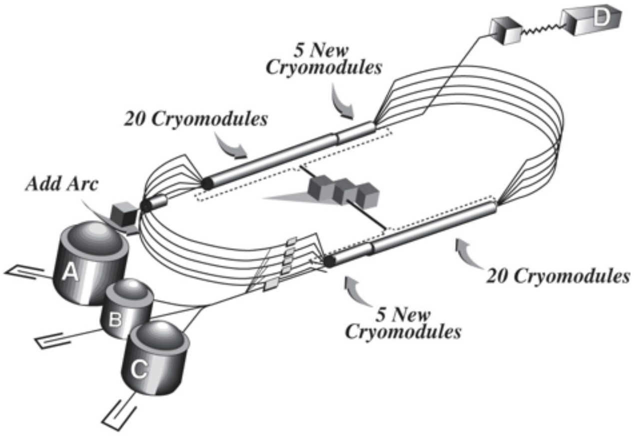

Figure 4: *The current CEBAF multi-pass electron accelerator at JLab, showing the three existing experimental Halls (A, B and C) and the planned Hall D.*

almost (loosely) monochromatic. This reduces the hadronic background from uwanted low energy photons and makes JLab unique. Even with only 10% of the eventual photon flux of 10^8/sec, the experiment will accumulate statistics during the first year of operation that will exceed published data with pions by at least an order of magnitude.

The linear polarization of the photons is important in carrying out the amplitude analysis needed to identify the J^{PC} of produced mesons and is essential in separating the production mechanism by natural parity exchange from unnatural parity exchange. The latter, for example, can be used to reduce backgrounds from dominant processes, such as diffractive production.

4 Amplitude Analysis on a Grid

Discoveries in particle physics, typically made at the frontiers of energy or precision, are facilitated by developments in technology. Likewise, the discovery of exotic hybrid mesons will require the development of a new paradigm for conducting precise analyses of large data sets. The data provide information on mesons decays, that can be theoretically described in terms of quantum mechanical amplitudes. Modern cyber infrastructure offers the opportunity to build an open access suite of services and data repositories that enable transparent analysis of data. Existing Grid-based tools will be utilized to move data and perform unbinned likelihood fits over multiple processors. The GlueX Collaboration is pursuing the development of such an infrastructure that would expedite collaboration among physicists by providing ready access to data and the fitting and visualization tools needed to conduct precision analyses of it, and it will be applied to existing data.

To identify the J^{PC} quantum numbers of a meson it is necessary to perform an *amplitude analysis*, which determines production amplitudes by fitting decay angular distributions. The fit includes information on the polarization of the beam and target, the spin and parity of the resonance, the spin and parity of any daughter resonances and any relative orbital angular momenta. The analysis seeks to establish the production strengths, production mechanisms and the relative phase motion of various production amplitudes.

There are both empirical and intrinsic difficulties in the implementation of such an analysis. Empirically, instrumentation effects, such as detector acceptance and resolution, can conspire to make one distribution look like another; intrinsic mathematical ambiguities exist for certain final states; and, backgrounds can limit one's ability to measure phase motion.

Another challenge lies in the selection of the amplitudes. For example, the analysis of the $\pi N \to \pi\pi\pi N$ reaction in the Brookhaven E852 experiment assumed the isobar model and processes like the Deck Effect (diffractive disassociation followed by quasi on-shell scattering) were not included. Another assumption admits a factorization within the isobar model that separates the production amplitude (to be fitted) from the (fixed) decay amplitude and much simplifies the numerical fit problem. As an application of the amplitude analysis toolkit, Deck-style production amplitudes will be implemented along with the familiar isobar model production amplitudes and fits will be run to expose the relative weights. The toolkit will be checked versus well established mesons in order to establish trustworthy error estimations.

5 The GlueX Detector

The GlueX detector (see Figure 5) is optimized for 8-9 GeV incident photons. Momentum analysis will be provided by a 2.2 T superconducting solenoid magnet. The use of a solenoidal spectrometer allows for the measurement of charged particles with excellent efficiency and momentum determination and the solenoidal field acts as a magnetic shield, containing the shower of unwanted electron-positron pairs associated with the photon beam. A 30 cm long liquid hydrogen vessel will be used as the production target.

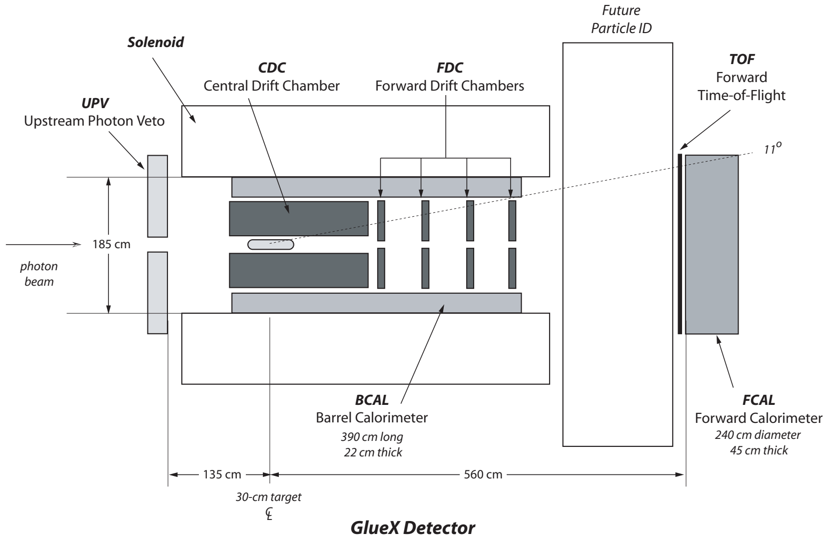

Figure 5: *A side-view schematic of the GlueX detector.*

5.1 Calorimetry

A circular lead glass array will serve as the forward ($\theta < 11^\circ$) electromagnetic calorimeter for the GlueX detector. An existing detector, the LGD used in the Brookhaven E852 experiment, will be reconfigured to this end. The circular stack matches the aperture of the solenoid and mimimizes the number of detector channels ($\sim$2800) while maximizing the target to FCAL distance.

BCAL will cover polar angles of $11^\circ < \theta < 126^\circ$ and will consist of alternating layers of thin (0.5 mm) lead sheets and 1-mm-diameter scintillating fibers. It will be segmented into 48 modules and will have a radiation length of 15.5 X_0. Beam test results from a prototype module exhibit performance characteristics for the energy and timing resolution that meet or exceed the design specifications, based on the KLOE calorimeter. However, the 2.2 T field places constraints on the readout of the BCAL. The only devices that can solve this problem in a field-resistant and compact manner are state-of-the-art silicon photodiodes, operating in limited Geiger mode. Novel, large-area (1.3 cm^2) units are currently in the R&D phase and show much promise.

5.2 Tracking

The system of tracking chambers in the GlueX detector must cover as close to a 4π solid angle as possible over a wide range of particle momenta and must have sufficient momentum resolution to be able to identify missing particles. Near the target it will provide very accurate vertex information. Finally, it is necessary that near the target the tracking can separate π's and K's up to about 0.5 GeV/c — a regime where dE/dx measurements will work.

The central drift chamber will track particles with polar angles between 20° and 170°, and is designed to minimize the material to traversing particles at forward angles. This straw-tube chamber will contain 3349 straws, each of which is 1.6 cm in diameter. The straws are arranged in 25 layers, eight of which will be stereo, tilted by ±6° from the straight tubes. The tubes are assumed to have an $r - \phi$ resolution of 150 μm, and a resolution along the length of the wire of about 200 $\mu\text{m}/\sin(6^\circ)$.

The forward drift chambers, FDC, are disk-shaped drift chambers, of outer radius 60 cm. The basic drift package of six layers of cathodes and anodes with 150 μm spatial resolution between two cathode strip planes. The strips are arranged in a u- and v-geometry with respect to the wires. The devices will provide 200 μm resolution and will have a total of ~ 12000 channels.

5.3 Particle Identification

Particle identification (PID) in GlueX will use input from nearly all of the detector systems in the experiment. Time-of-flight information will be obtained from both BCAL and the forward TOF system. The latter will consist of two walls of scintillator bars oriented perpendicular to each other; the bars will be 2.52 m long and have a 6 cm width and 2.54 cm thickness. A future PID device will provide information on forward going tracks while the CDC will provide dE/dx information. In order to effectively use all of this information, GlueX plans to develop of likelihood-based PID system coupled to kinematic fitting to perform a global PID.

6 Summary

The nature of confinement is an outstanding and fundamental question in QCD. Lattice QCD and phenomenology strongly indicate that the gluonic field between quarks forms flux tubes and that these qualitatively account for confinement. The excitation of the gluonic field leads to an entirely new spectrum of mesons having exotic J^{PC} quantum numbers, with properties predicted by QCD. Data and sophisticated amplitude analysis tools are required to validate these predictions. The definitive experiment for this search will be GlueX at the energy-upgraded Jefferson Lab.

7 Acknowledgements

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