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Mapping gluonic excitations and confinement

The GlueX/Hall D project at Jefferson Lab

A.R. Dzierba[a]

Department of Physics, Indiana University, Bloomington, IN 47405, USA

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Abstract. One of the outstanding and fundamental questions in physics is the quantitative understanding of the confinement of quarks and gluons in quantum chromodynamics (QCD). Confinement is a unique feature of QCD. Exotic hybrid mesons manifest gluonic degrees of freedom and their spectroscopy will provide the crucial data needed to test assumptions in lattice QCD and phenomenology leading to confinement. Photoproduction is expected to be particularly effective in producing exotic hybrids but data using photon probes are sparse. At Jefferson Lab, plans are underway to use the coherent bremsstrahlung technique to produce a linearly polarized photon beam. A solenoid-based hermetic detector will be used to collect data on meson production and decays with statistics that will exceed the current photoproduction data in hand by several orders of magnitude after the first year of running. In order to reach the ideal photon energy of 9 GeV/c for this mapping of the exotic spectra, the energy of the Jefferson Lab electron accelerator, CEBAF, will be doubled from its current maximum of 6 GeV to 12 GeV. The physics and project are described.

PACS. 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 13.60.Le Meson production

1 Science of confinement

The observation nearly four decades ago that mesons are grouped in nonets, each characterized by unique values of J^{PC} —spin (J), parity (P) and charge conjugation (C) quantum numbers— led to the development of the quark model. Within this picture, mesons are bound states of a quark (q) and antiquark ($\bar{q}$). The three light-quark flavors (*up*, *down* and *strange*) suffice to explain the spectroscopy of most —but not all— of the lighter-mass mesons (*i.e.* below 3 GeV/c^2) that do not explicitly carry heavy flavors (charm or beauty). Early observations yielded only those J^{PC} quantum numbers consistent with a fermion-antifermion bound state. The J^{PC} quantum numbers of a $q\bar{q}$ system with total quark spin, $\boldsymbol{S}$, and relative angular momentum , $\boldsymbol{L}$, are determined as follows: $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$, $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. Thus, J^{PC} quantum numbers such as 0^{--}, 0^{+-}, 1^{-+} and 2^{+-} are not allowed and are called *exotic* in this context.

Our understanding of how quarks form mesons has evolved within quantum chromodynamics (QCD) and we now expect a richer spectrum of mesons that takes into account not only the quark degrees of freedom but also the gluonic degrees of freedom. Gluonic mesons with no quarks (*glueballs*) are expected. These are bound states of gluons and since the quantum numbers of low-lying glueballs are not necessarily exotic, they should manifest themselves as extraneous states that cannot be accommodated within $\bar{q}q$ nonets. But their identification is complicated since they do mix with $\bar{q}q$. Excitations of the gluonic field binding the quarks can also give rise to so-called *hybrid* mesons that can be viewed as bound states of a quark, antiquark and valence gluon ($q\bar{q}g$). An alternative picture of hybrid mesons, one supported by lattice QCD [1], is one in which a gluonic flux tube forms between the quark and antiquark and the excitations of this flux tube lead to so-called *hybrid* mesons. Actually the idea of flux tubes, or strings connecting the quarks, originated in the early 1970s [2] to explain the observed linear dependence of the mass-squared of hadrons on spin (Regge trajectories). Conventional $\bar{q}q$-mesons arise when the flux tube is in its ground state. Hybrid mesons arise when the flux tube is excited and some hybrid mesons can have a unique signature, exotic J^{PC}, and therefore the spectroscopy of exotic hybrid mesons is not complicated by possible mixing with conventional $\bar{q}q$ states.

The level splitting between the ground-state flux tube and the first-excited transverse modes is π/r, where r is the separation between the quarks, so the hybrid spectrum should lie about 1 GeV/c^2 above the ground-state spectrum. According to the flux tube model [3] and lattice

[a] *Present address*: Department of Physics, Indiana University, Bloomington, IN 47405 USA; e-mail: `dzierba@indiana.edu`

gauge calculations [4], one expects the lightest $J^{PC} = 1^{-+}$ exotic hybrid to have a mass of about 1.9 GeV/c^2.

In this discussion the motion of the quarks was ignored, but we know from general principles [3] that the an approximation that ignores the impact of the flux tube excitation and quark motion on each other seems to work quite well.

In the coming years there will be significant computational resources [5], using lattice techniques, dedicated to understanding non-perturbative QCD including confinement. The prediction of the hybrid spectrum, including decays, will be part of this program but experimental data will be needed to validate assumptions. The spectroscopy of exotic mesons provides a clean and attractive starting point for the study of gluonic excitations.

2 Experimental situation

After about two decades of experimental searches there have been reports of observations of states with $J^{PC} = 1^{-+}$ by the Brookhaven E852 Collaboration. One of these was reported in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ using an 18 GeV/c π^- beam. The state has a mass of (1593 ± 8) MeV/c^2 and width of (168 ± 20) MeV/c^2 and decays into $\rho^0\pi^-$ [6]. A partial-wave analysis (PWA) of the 3π system uncovered the exotic signal as a P-wave between the ρ^0 and π^- with a line shape in the P-wave amplitude and interference with the nearby $\pi_2(1670)$ ($J^{PC} = 2^{-+}$) characteristic of a Breit-Wigner resonance. The exotic state's contribution to the 3π spectrum is much smaller than the dominant $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ so uncovering the signal is a challenge.

The E852 Collaboration also reported observation of another $J^{PC} = 1^{-+}$ state with mass (1370 ± 16) MeV/c^2 and a width of (385 ± 40) MeV/c^2 decaying into $\eta\pi^-$ [7] and soon after confirmed by the Crystal Barrel group [8] but this result is not without controversy. If an $\eta\pi$ system exists in a P-wave it has exotic J^{PC} but the identification of a Breit-Wigner resonance is particularly challenging since the $a_2(1320)$ dominates the $\eta\pi$ spectrum. Critical to the identification of an exotic state is not only showing the presence of a P-wave, but also that the resulting line shape is consistent with a Breit-Wigner and that the phase motion of the P-wave, as determined by its interference with the dominant D-wave, cannot be due solely to the $a_2(1320)$-resonance. A recent analysis of E852 data from the reaction $\pi^- p \to \eta\pi^0 n$ indicates that a P-wave is present but is not consistent with a Breit-Wigner resonance [9] and is likely due to final-state re-scattering. This reaction has some advantages. Both the $a_0(980)$ and $a_2(1320)$ are produced and this aids in the PWA and for $\eta\pi^0$ —in contrast to $\eta\pi^-$— C, charge conjugation, is well defined.

3 Using photons as probes

The data to date are tantalizing and suggest that exotic hybrid mesons may exist but the extensive data collected to date with π probes have not uncovered the hybrid meson spectrum. Lattice QCD and phenomenology, however, indicate the photon is a probe that should be particularly effective in producing exotic hybrids but data on photoproduction of light mesons are sparse indeed.

The first-excited transverse modes of the flux tube are degenerate and correspond to clockwise or counterclockwise rotations of the flux tube about the axis joining the quark and antiquark fixed in space with $J = 1$ [3]. Linear combinations of these two modes are eigenstates of parity and lead to $J^{PC} = 1^{+-}$ and $J^{PC} = 1^{-+}$ for the excited flux tube. When these quantum numbers are combined with those of the $q\bar{q}$ with $\boldsymbol{L} = 0$ and $\boldsymbol{S} = 1$ (quark spins aligned), three of the six possible J^{PC} have exotic combinations: 0^{+-}, 1^{-+} and 2^{+-}. A photon probe is a virtual $q\bar{q}$ with quark spins aligned. In contrast, when the $q\bar{q}$ have $\boldsymbol{L} = 0$ and $\boldsymbol{S} = 0$ (spins antialigned), the resulting quantum numbers of the hybrid meson are not exotic. Pion probes are $q\bar{q}$ with quark spins antialigned. If we view one outcome of the scattering process as exciting the flux tube binding the quarks in the probe, the suppression of exotic hybrids in π-induced reactions is not surprising —a spin-flip of one of the quarks is required followed by the excitation of the flux tube. In contrast, the spins of the virtual quarks in the photon probe are properly aligned to lead to exotic hybrids. Phenomenological studies quantitatively support this picture predicting that the photoproduction cross-sections for exotic mesons are comparable to those for copiously produced mesons such the $a_2(1320)$ [10,11].

4 The GlueX/Hall D project

Based on this guidance from theory and experiment, the GlueX/Hall D Collaboration was formed to design a photon beam and detector to map the exotic hybrid spectrum [12,13]. The goal of the experiment is to reach meson masses up to about 3 GeV/c^2 and collect sufficient statistics on the production of mesons with a sensitivity to a wide variety of decay modes. In order to identify the quantum numbers, the PWA technique will be used. This requires a detector that has excellent resolution, is hermetic and has good rate capability. It is essential to kinematically identical exclusive reactions in order to apply PWA.

4.1 Photon beam

The optimal photon energy for this study is around 9 GeV. The photon energy must be large enough to produce the higher mass states with sufficient boost in the laboratory so that their decay products will be detected and measured with sufficient resolution. It is also important that the energy be high enough to avoid line shape distortions that arise due to relatively large values of $|t_{\min}|$ occurring near threshold —$|t_{\min}|$ is the minimum momentum transfer squared from the incident photon beam to the produced meson.

As will be described below, a solenoid-based detector design will be used. This represents the optimal design for fixed-target photoproduction experiment as the intense photon beam produces large electromagnetic backgrounds (e^+e^- pairs) that can be trapped within a tight region along the beam by the axial field of the solenoid. However, with this geometry, the momentum resolution of two-body decays of lighter mesons degrades if the photon beam energy exceeds 9 GeV/c^2.

The photon beam must also be linearly polarized due to the PWA requirements. This is related to the fact that states of linear polarization, in contrast to states of circular polarization, are eigenstates of parity. The linear polarization of the photon beam will also be used as an exotics filter [14].

Coherent bremsstrahlung will be used to produce linearly polarized photons. Instead of using an amorphous radiator, a diamond crystal is used. At special settings for the orientation of the crystal with respect to the electron beam, 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. The resulting spectrum of photons is a sum of incoherent bremsstrahlung, whose spectrum falls like $1/E_\gamma$, and the coherent spectrum. The correlation of emitted photon energy and angle also allows one to substantially collimate out the incoherent portion of the photon spectrum before the photons reach the detector. A collimator with a 3.4 mm diameter hole placed 80 m from the radiator will be used to greatly reduce the backgrounds from unwanted lower-energy photons in the detector target. The collimation is also needed to increase the degree of linear polarization to 40% in the current design. The employment of coherent bremsstrahlung and collimation is made possible by the superb characteristics of the electron beam at Jefferson Lab including the continuous wave feature leading to a duty factor close to unity, the small spot size and the emittance characteristics. In addition, recent advances in growing and thinning diamond wafers down to 20 μm result in negligible multiple scattering allowing collimation to be effective.

The diamond crystal in the electron beam will be immediately followed by a focal-plane spectrometer (photon tagger) that will be used to measure the electron energy after the radiator thus allowing an energy determination of each photon into the detector with a resolution of 0.1%.

4.2 Accelerator upgrade

In order to produce 9 GeV photons with sufficient degree of linear polarization an electron energy of 12 GeV will suffice. For example, increasing the electron energy to 20 GeV will only double the degree of polarization of 9 GeV photons from 40% to 80% while requiring a major modification of the accelerating section and arcs. However, dropping from 12 GeV to 10 GeV electrons would reduce the degree of linear polarization of 9 GeV photons by nearly an order of magnitude.

Figure 1 shows the configuration of the proposed 12 GeV CEBAF upgrade at Jefferson Lab. The present CEBAF accelerator consists of two linear accelerating sections, each about 250 m long. Re-circulating arcs of magnets allow multiple-passes of the electrons through the accelerating regions. Currently, beam is delivered to three existing experimental halls labelled A, B and C. The proposal calls for the construction of a fourth hall (D) preceded by the photon tagger to which 12 GeV electrons will be delivered. To accomplish the energy upgrade 5 new accelerating superconducting cryomodules will be added to the 20 existing cryomodules in each of the two accelerating sections. The space for the additional modules already is available. In addition, 3 of the existing 20 cryomodules in each of the two straight sections will be replaced. A tenth added arc will allow for 11 full passes of the electrons before delivery to Hall D. More details of the accelerator upgrades along with the proposed GlueX/Hall D project and the planned upgrades for the existing halls for the upgrade project are described in ref. [15].

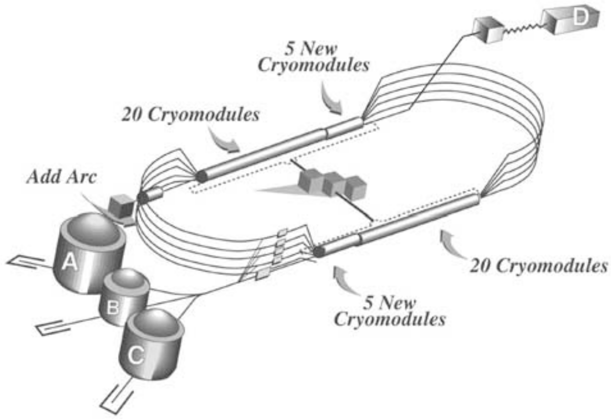

Fig. 1. The proposed configuration for the 12 GeV upgrade of CEBAF at Jefferson Lab showing the additional new Hall D for the GlueX experiment. Details are given in the text.

4.3 Detector

Figure 2 shows a schematic of the proposed detector for Hall D. Central to the detector is a superconducting solenoid with a clear bore diameter of 73 in and a length of 183 in. The central field is 2.5 T. The magnet was originally constructed for the LASS experiment at SLAC and then moved to LANL where it was used for the MEGA experiment. It will be moved, refurbished and shipped to Jefferson Lab for use in the GlueX/Hall D experiment. The inside bore of the solenoid will be lined with an electromagnetic calorimeter surrounding the target and the central and forward particle tracker. That will be followed by an atmospheric Čerenkov counter, a time-of-flight wall and then a 2500-element lead glass calorimeter. The latter was originally built and used in the E852 experiment and has since been moved to Jefferson Lab for the GlueX/Hall D experiment.

Initially the detector will run with an incident photon flux of 10^7 photons per second. With this flux and after the first year of data-taking, the collected sample will

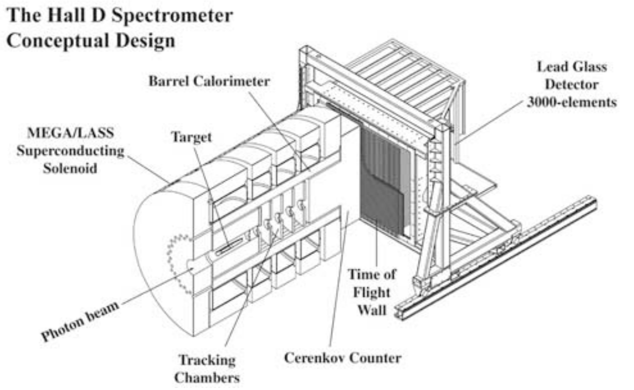

Fig. 2. The conceptual design for the proposed GlueX/Hall D project. Details are given in the text.

exceed current photoproduction data by several orders of magnitude and current π-induced data by an order of magnitude. Later the beam flux will be increased by a factor of 10. Data will be recorded at the rate of 100 MB/s leading to roughly 1 PetaByte of stored data per year. This is comparable to the size of the data sets planned for the LHC experiments.

4.4 Plan for analysis

Extensive Monte Carlo studies have been carried out to evaluate the proposed detector design. The acceptance of the proposed detector over relevant kinematic variables including decay angles is high and uniform. Double-blind Monte Carlo studies have included exotic signals at low levels mixed with conventional mesons. Generated events have been smeared according to the expected resolution and passed through acceptance simulations. The surviving sample has then been acceptance corrected, reconstructed and passed through PWA-fitting programs. Signals at the few percent level have been successfully recovered.

In addition to Monte Carlo studies, the fundamental assumptions behind the PWA are also under study including any model assumptions (*e.g.*, the *isobar* assumption), mathematical ambiguities, and issues of analyticity. It is essential to minimize possible biases and uncertainties from the dynamical unknowns.

5 Conclusions

The question of the quantitative understanding of the confinement mechanism in QCD is still an open, important and fundamental issue in physics. There has been recent impressive theoretical progress on this issue and ambitious plans are underway to significantly increase the computational resources for lattice QCD leading to further progress. Data on the spectrum of gluonic excitations is essential in this effort —experiment is the ultimate arbiter. Although some tantalizing data suggest that gluonic excitations have been uncovered, their detailed mapping awaits new data from photoproduction which is expected to be a rich source. The energy upgraded CEBAF at Jefferson Lab, along with the construction of a new photon beam and detector dedicated to spectroscopy will provide the unique opportunity to carry out the definitive experiment. This has been recognized in the recent long-range plan for nuclear science in the next decade in the US [16].

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