Confinement and Exotic Meson Spectroscopy at 12GeV JLAB

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Phenomenology of gluonic excitations and possibilities for searches of exotic mesons at JLab are discussed.

I Introduction

Quantum chromodynamics (QCD) represents part of the Standard Model which describes the strong interactions. The fundamental degrees of freedom are quarks – the matter fields, and gluons – the mediators of the strong force. Quarks and gluons are permanently confined into hadrons, *e.g.* protons, neutrons and pions, to within distance scales of the order of $1fm = 10^{-15}m$. Hadrons are bound by residual strong forces to form atomic nuclei. Thus QCD determines not only the quark-gluon dynamics at the sub-subatomic scale but also the interactions between nuclei at the subatomic scale and even the nuclear dynamics at a macroscopic level, *e.g.* at distances of the order of 10^4m, specific to typical sizes of neutron and possible quark stars.

It is quite amazing that dynamics in such distant regimes are all determined by essentially one parameter – the strength of the QCD interaction. As in any local field theory the interaction strength is a function of the energy-momentum of the interacting particles. In QCD this "running" coupling decreases at high energy ("asymptotic freedom") leading, for example, to the Feynman parton model. On the other hand, the strength of soft interactions is strong resulting in quark and gluon confinement. An implication of confinement is that a single quark cannot be separated from other strongly interacting (colored) objects, and thus the physical hadronic spectrum contains only color-neutral hadrons. Unlike quantum electrodynamics, in QCD the force carriers (gluons) also carry charge(color) and thus can directly interact with each other without matter (quarks) being exchange. Since the interaction strength is large for object moving around on a typical hadronic scale of $1fm$, one expects there to be bound states of pure radiation (glueballs) or a mix of quark-gluon excitations (hybrids).

The computational challenge in QCD steam from the fact that it is a relativistic, quantum, strongly-interacting many-body system. In the soft domain direct calculations in QCD come primarily from numerical simulations using discrete space-time lattice which reduces the initially infinite number of degrees of freedom to a finite, albeit large $O(10^4)$ number. For technical reasons dynamical evolution is studied by replacing the Minkowski by the Euclidean metric thereby converting to a statistical systems and using Monte Carlo methods to evaluate the partition function.

In parallel many analytical many-body techniques have been employed to identify effective degrees of freedom and numerous approximation schemes have been advanced to describe the soft structure and interactions of hadrons, *e.g.* the constituent quark model, bag and topological soliton models, QCD sum rules, chiral lagrangians, etc.

In this talk I will focus on the physics of soft gluonic excitations and their role in quark confinement. Gluons carry the strong force, and since on a hadronic scale the light u and d quarks, which make the ordinary nuclear matter are essentially massless, the bulk of the normal mass in the universe originates from self interactions among gluons. From high energy experiments, which are sensitive to the short distance interactions, it has been inferred that gluons do carry a large (50%) fraction of the proton's momentum and spin. Except for the strong charge – color, gluons do not carry any other charge *i.e.* electromagnetic or weak, and in the absence of colored probes (confinement) there are no external probes which could be used to directly "poke" the gluons inside hadrons. It is therefore only the spectroscopic information that can give insight into the role and nature of the soft gluons. Since the gluon field is responsible for confining the valence quarks, spectroscopy of gluonic excitations could also provide the ultimate insight into the dynamical origins of confinement.

II Relating gluon dynamics to confinement

The connection between gluonic excitations and confinement has been extensively studied using numerical simulation (lattice). For example, there exist numerical simulations of the energy of the gluonic excitations in a system containing a static quark and antiquark pair. The ground state configuration of the gluonic field results in an effective potential between the sources, which as a function of the separation between the sources is well approximated by the standard Cornell potential, $V(r) = -\alpha/r + br$ The first exited state of the gluonic field turns out to have one unit of total angular momentum along the axis connecting the static color sources, and has a negative product of parity and charge conjugation [1]. This is against a naive, perturbative picture with the gluonic field described as a vector particle. Even if such a "constituent" gluon is to be bound to the quark sources by normal two-body forces, the resulting energy of the lowest S-wave, positive parity configuration is lower then the P-wave configuration in contrast to the lattice results [2] . This inconsistency can be resolved by formulating the "constituent" gluon picture starting from QCD canonically quantized in the Coulomb gauge [3].

Combining the quantum numbers of the low-lying gluon excitation with those of the quark-antiquark pair leads to a spectrum of hybrid mesons. Among those there are the so called exotic hybrid mesons, or exotics. These have quantum numbers, spin, parity and charge conjugation, J^{PC} that cannot originate from the valence quark and antiquark alone, *e.g.* $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \cdots$ .. The J^{PC} of a quark-antiquark system is given by $\vec{J} = \vec{S}_{q\bar{q}} + \vec{L}_{q\bar{q}}$, $P = (-1)^{L_{q\bar{q}}+1}$, and $C = (-1)^{S_{q\bar{q}}+L_{q\bar{q}}}$ where $\vec{S}_{q\bar{q}} = \vec{S}_q + \vec{S}_{\bar{q}}$ is the total spin ($S_{q\bar{q}} = 0, 1$) of the pair and $L_{q\bar{q}} = 0, 1, 2, \cdots$ is the relative orbital angular momentum. Thus an exotic cannot mix with an ordinary meson and an experimental evidence of an exotic resonance would be the "smoking gun" signal for presence of non-valence degrees of freedom in a hadron. There is good evidence from lattice computations that the additional contribution to exotic meson structure should originate from exciting the gluonic field rather then from breakup channels . *e.g.* four-quark states. The exotic $J^{PC} = 1^{-+}$ state arises from combining the orbitally excited gluon field, which contributes to the first excited adiabatic potential shown with the $L = 0, S = 1$ quark-antiquark configuration.

From lattice simulations of light quark exotics follows that the $J^{PC} = 1^{-+}$ is the lightest exotic state and it is slightly below 2 GeV [4, 5, 6]. Similarly, studies of the charmonium exotics indicate that the excitation of the gluonic degrees of freedom requires approximately 1 GeV. One should keep in mind however, that the masses computed on the lattice are obtained with rather heavy u and d quark masses, > 50 MeV. Extrapolation to the chiral limit can shift downward the predicted hadron masses by $100 - 200$ MeV [7].

An identification of exotic resonances can only be made if they are not too broad. This indeed is expected to be the case based on studies of exotic mesons widths in the limit of a large number of colors [8]. Studies of the ground state exotic meson wave function on the lattice also show that it is well confined to a region where pair creation and string breaking is not expected to be significant [9].

To summarize, the current lattice and phenomenological studies indicate that the lightest exotic meson should have $J^{PC} = 1^{-+}$, mass between $1.8 - 2$ GeV and a typical hadronic width of $100 - 200$ MeV.

III The $J^{PC} = 1^{-+}$ exotic spectrum

From theoretical point of view some of the reported exotic meson candidates are suspicions. The E852 collaboration has reported a 1^{-+} exotic resonance in $\eta\pi^-$ and $\eta'\pi^-$ decay channels with widths of the order of 350 MeV and masses 1.4 and 1.6 GeV respectively. The experiment used 18 GeV π^- beam on a hydrogen target and resonances were identified via the partial wave analysis [10]. The Crystal Barrel experiment also found a signature of an exotic wave in the $\eta\pi$ system consistent with the E852 result [11]. The $\eta\pi$ channel is particularly suited for exotic meson identification since the $\eta\pi$ P-wave has exotic quantum numbers. However, recent analysis which takes into account other angular correlations ignored in the previous analysis shows that the resonance interpretation of the exotic wave in the $\eta\pi$ is indeed problematic [12].

In contrast, the exotic signal seen in the decay to $\rho\pi$ has both mass and width which is more in line with theoretical expectations. If this is so, the E582 data indicates that the exotic is weakly $O(few\%)$ produced in pion induced reactions as compared to, for example, production of a nearby a_2 non-exotic resonance. As discussed above, the 1^{-+} exotic is expected to have the quark-antiquark system in the spin-1 configuration, and thus one indeed expects its production to be suppressed in a peripheral process with pion beams. In such processes, the structure of the produced resonance is primarily driven by that of the beam which scatters of the meson cloud around the nucleon. Thus if the pion beam is replaced by a photon beam, which acts as a virtual quark-antiquark pair in the spin-1 state, one expects the exotic production to be enhanced. This has recently been shown to be the case [13, 14].

IV Exotic meson studied at 12GeV JLab

The data on meson photoproduction is very limited, mainly due to technical challenges in producing high intensity, polarized photon beams. Nowadays the CEBAF electron accelerator at the Jefferson Lab has the potential to deliver very high quality electron beam which using the coherent bremsstrahlung technique can be turned into a linearly polarized photon beam. In order to perform exotic mesons photoproduction studies the energy of the accelerator has to be upgraded from the current 6 to 12 GeV, to produce $8 - 9$ GeV photons which is the optimal energy for covering the exotic mesons spectrum in the $1.5 - 2.5$ GeV mass range.

In one year of running the yields for exotic mesons production are expected to produced 250K exotic mesons which is $O(10^3)$ more then currently collected by the E852 experiment. With a hermetic detector with full event reconstruction capabilities even a weak exotic signal (on order of magnitude weaker then expected for photoproduction) can be well identified.

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