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Low energy hadron phenomenology

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Abstract. This talk discusses some of latest theoretical, phenomenological and experimental results is hadron spectroscopy.

1. Introduction

In the past few years we have witnessed spectacular new discoveries and advances in strong interaction physics. The Relativistic Heavy Ion Collider (RHIC) discovery of the "perfect fluid" formed by quarks and gluons inspired a new field of applications of string theory-particle physics duality. Novel types of bound states are the likely explanation for the "X,Y,Z" states appearing in few-hadron systems. Large-scale numerical simulations (lattice gauge theory) are now on the verge of understanding the physical origin of visible matter in the universe. The unique features of the underlying theory of strong interactions, Quantum Chromodynamics (QCD), forms an attractive template for physics beyond the Standard Model, which has recently been validated by the discovery of the Higgs particle.

Developments in particle accelerators and detection techniques have led to a new generation of experiments in hadron physics that are flourishing around the world. These facilities and experiments include existing laboratories such as BESIII in China, COMPASS at CERN, RHIC in the US, VES in Russia, and Belle in Japan; JLab in the US and PANDA in Germany, which are in construction and upgrade phases, and future facilities under discussion such as EIC in the US and B-factories.

Confinement is the distinguishing feature of QCD. It seems to forbid isolated elementary quarks and gluons to exist freely in nature. Understanding the origin of confinement is one of the fundamental questions in physics [1] . Hadrons are the bound states of quarks and gluons allowed by confinement. Studies of individual hadrons and their interaction offer a unique window into this fundamental phenomenon. In this talk I focus on recent theoretical and phenomenological advances in understanding confinement and illustrate how future experiments in hadron physics will help us understanding confinement. The new experiments at the various hadron facilities will generate complicated data sets, which demand a qualitatively new level of sophistication in analysis never before achieved. I will discuss

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some of the methodology that needs to be developed to take full advantage of the information contained in the experimental data.

2. Properties of confinement

The common notion that confinement is equivalent to non-existence of free quarks is not totaly accurate. In principle with absence of free quarks alone one cannot tell if quarks are confined or if they are screened, which makes them effectively them "invisible" to external probes. What distinguishes the two possibilities is how the energy is stored in the gluon field produced by the quarks. In a confined theory energy of a single quark is expected to be infinite. A finite energy of a color neutral system is possible as long as color flux lines begin and end on nearby sources. As the separation between quarks increases the flux lines stretch. If the flux tubes have a constant energy per area the total energy will increase linearly with quark separation. At some point it will become energetically favorable for a stretched flux tube to break and to convert its energy into production of quark-antiquark pairs. This is a possible mechanism for strong decays of hadrons. Spectrum of hadrons can therefore reveal not only the properties of the gluon flux but also about its excitations.

Properties of QCD flux lines can be studied numerically when they are attached to static quarks [2–5]. Infinitely heavy quarks act as external sources and cannot be pair-produced. Using lattice simulations it was possible to confirm the confining nature of the potential between static color sources as well as to determine flux-tube nature of the chromolectric field between quarks. What are the mechanisms responsible for formation of the color flux is currently a subject of intense investigations [6, 7]. This question is addressed, for example in lattice simulations by examining contributions from various gluon field configurations to the quark potential. Using various "filtration" methods it has been shown that flux tubes are most likely due to condensation of chromomagnetic domains. If this is the case one may think of the QCD vacuum as a dual supperconductor, *i.e.* a conductor with the roles of magnetic and electric fields interchanged. The non-abelian nature of QCD, however, complicates this simple analogy and makes unique identification of domains difficult. It is worth noting, that this "many body" confinement scenario seems incompatible with "few body" models of confinement that are based on the idea that long range forces may originate from a dressed, one-gluon exchange. In fact lattice simulations unambiguously show that gluons do not propagate long distances [8]. Thus inside hadrons, gluons play a dual role of providing confining for quarks and being confined themselves. Being gauge dependent, identification of the corresponding gluon field componenets is not unique. The Coulomb gauge maybe particularly suitable for such studies [9–11]. The QCD analog of the instantaneous Coulomb potential depends on the distribution of the gluon field and in a magnetic condensate may lead to a long range force [12]. The remaining transverse gluon components propagate as massive particles and have properties similar to constituent quarks [13].

3. Hybrid mesons

Quantum numbers of ordinary mesons are obtained by combining quantum numbers of the quark and the antiquark. For a specific quark flavor, the spin, parity and, in the case of neutral mesons, charge conduction are given by $\vec{J} = \vec{S} + \vec{L}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, with $L = |\vec{L}|$ being the relative orbital angular momentum and $S = |\vec{S}| = 0, 1$ the total quark spin. From these relations it follows that certain combinations of the J^{PC}'s cannot be associated with a $q\bar{q}$ state, *e.g.* $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \cdots$. These are referred to as exotic. In general exotics must contain other degrees of freedom besides the valence quarks. Numerous studies of exotics spectrum have been made using a variety of phenomenological models [14–21], but only recently, with advances in lattice gauge simulation we have a much stronger evidence that such states might indeed exist [22–27]. It should be noted, nevertheless that hybrids, just like other ordinary $q\bar{q}$ states with masses above open decay channels become unstable resonances, and therefore are not directly accessible nether to experiment nor to numerical simulation. Various methods for extrapolation "beyond the real axis" can be used to identify a resonant state. In particular in the case of the lattice, which suffers from lack of rotational symmetry, finite volume effects, chiral extrapolation issues, *etc.* novel methods are at present vigorously explored [28–34]. It is important to note that even without the full machinery for mapping resonance poles of the scattering amplitude onto the finite volume lattice spectrum implemented, the existing finite volume signatures of hybrid meson are just as robust he signatures of other well established $q\bar{q}$ resonances *e.g.* the ρ meson.

The resent lattice simulations of hadron spectrum were discussed by J. Dudek at this meeting. Independent of the quark mass and flavor, lattice computations indicate that there might be a multiplet of hybrid mesons located between the first and the second resonance region, which contains nearly degenerated states with $J^{PC} = 0_h^{-+}, 1_h^{--}, 2_h^{-+}, 1_h^{-+}$ quantum numbers (with the subscript h appended to distinguish them from the regular quark-model states), including the 1_h^{-+} as the lightest exotic.

4. Hybrids in Coulomb gauge

The appearance of a four-state hybrid meson multiplet was predicted in [35, 36] in a model based on the analysis of the gluon spectrum of canonically quantized QCD in the Coulomb gauge. In a pure YM with static quarks, the Coulomb gauge calculation of the spectrum of gluon excitations gives results [5], which are consistent with lattice determination of the quark-antiquark adiabatic potentials [2–4]. In particular, as the relative separation between the quark and the antiquark is taken to zero, the excited gluon field forms a state referred to as a gluelump. Lattice determination of the gluelump spectrum shows that the lowest energy state has quantum numbers of $J^{PC}_{glue} = 1^{+-}$ [37]. This is quite an unexpected result, since the gauge field describes a 1^{--} gluon. The appearance of the 1^{+-} as the lowest energy state corresponds to a 1^{--} gluon bound to the static, $q\bar{q}$ color octet in a P-wave orbital. Indeed, it can be shown that the non-abelian Coulomb potentials reverses the order of even and odd-parity orbitals, pushing the S-wave above the P-wave. The appearance of a four-state lowest multiplet of hybrids can therefore be explained. These hybrids contain the ground state constituent, color-octet $q\bar{q}$ pair and the ground state 1^{+-} quasi-gluon. Coupling J^{PC}'s of the quark pair, $J^{PC}_{quark} = 0^{-+}$ or 1^{--} corresponding to zero orbital angular momentum and $S = 0, 1$, respectively, to the gluon J^{PC}'s yields precisely the quantum numbers of lattice hybrids discussed in Sect. 3.

One can push this phenomenology further, by considering radiative transitions [23]. The multipole (low-photon energy) expansion may be an adequate approximation for transitions between hybrids and the ground state or first excited $q\bar{q}$ mesons. Photon emission has both quark spin-flip and non-flip components. The former is a relativistic effect $O(1/m)$ and it is suppressed for emissions from heavy quarks. Indeed, the measured radiative decay widths of the leading, $M1$ quark-spin flip transitions between $q\bar{q}$ states, *e.g.* $J/\psi(1^{--}) \to \gamma\eta_c(0^{-+})$) are of the order of a few keV's, while for the non-flip $E1$ transitions, *e.g* $\chi_{c0}(0^{++}) \to \gamma J/\psi(1^{--})$ are $O(100)$ keV.

The quark-spin content of the non-exotic low lying hybrids, is predicted to be exactly opposite to that of the corresponding $q\bar{q}$ mesons. That is, the vector hybrid has $S = 0$ and pseudo-scalar and pseudo-tensor have $S = 1$ while the $q\bar{q}$ vector has $S = 1$ and the other two $S = 0$. Thus the order of magnitude of the magnetic dipole, $M1$ transitions from the four hybrids (including the exotic) are expected to be larger than the $M1$ transitions between $q\bar{q}$ states and similar to the electric dipole $E1$ transitions between $q\bar{q}$ mesons. Ignoring hyperfine interactions the four lightest hybrids are near degenerate and have similar orbital wave functions. Thus the following decays are expected to have similar $M1$ matrix elements [38], for $(S = 1) \to \gamma(S = 1)$: $0_h^{-+} \to \gamma 1^{--}$, $1_h^{-+} \to \gamma 1^{--}$, $2_h^{-+} \to \gamma 1^{--}$ and for $(S = 0) \to \gamma(S = 0)$, $1^{--} \to \gamma 0^{-+}$ with widths, for charmonia in the range $\Gamma = 10$–100 keV.

5. Experimental status

In recent years, BaBar, Belle, BESIII and CDF have all reported possible signatures of charmonium-like states, which do not fail into the quark model classification [39]. One of the latest additions to the new "XYZ" resonance category is the charged chromium state, the $Z_c^{\pm}(3900)$ seen in the mass spectrum of the $J/\psi\pi^{\pm}$ events from the $Y(4260) \to J\psi\pi^+\pi^-$ decay [46, 47]. The $Y(4260)$ is also one of these new states and it is by now rather well established. It was discovered by BaBar [40] through initial state radiation in e^+e^- annihilation and confirmed by Belle [41] and CLEO [42]. There have been attempts to associate the $Y(4260)$ with a quark model state [43]. The problem is that nearby quark-model "slots" in the $4S$ and $2D$ multiplets are more likely to be associated with the $\psi(4415)$ and $\psi(4160)$, respectively. In fact the $Y(4260)$ is the natural candidate for the 1_h^{--} hybrid state discussed above. There is also a candidate for the $s\bar{s}$ analogue, the $Y(2175)$ seen by Belle [44]. In the light quark sector, searches have focused on hybrids with exotic quantum numbers, specifically the 1_h^{-+}. A review of the experimental results can be found in [45]. The most recent sighting comes from the measurement by the COMPASS collaboration [48] of the $\eta'\pi$ angular distribution as a function of the pair's invariant mass in the reaction $\pi^- p \to \eta'\pi^- p$. The $\eta'\pi$ system in the relative P-wave has the 1^{-+} exotic quantum numbers thus a resonance in this system in the mass range $1.6 - 2$ GeV would be a natural candidate for lightest exotic. In the past the VES collaboration [49] reported a strong intensity and phase motion characteristic to a broad resonance. The E852 experiment at BNL [50] also found a likely resonance with parameters consistent with the VES measurement. By fitting the intensity and phase of the $\eta'\pi$ P-wave to a Breit-Wigner resonance E852 determined the mass and width of the exotic resonance to be $M = 1.597^{+0.045}_{-0.010} \pm 0.010$, $\Gamma = 0.340 \pm 0.50 \pm 0.04$.

6. Amplitude analysis

Establishing existence of resonances requires a search for resonance poles in the complex energy plane. To do this conclusively, from experimental data, requires the development of theoretical reaction amplitudes, which can be analytically continued outside the physical region of the kinematical variables: energies, momenta, and angular momenta. The first appearance of hadron physics at the forefront of high-energy research occurred 40 years ago. At that time, experimental datasets were sparse, computational resources were scarce, and the real degrees of freedom of the strong interaction, along with its unique properties, were just being identified. In spite of these limitations, a great deal of understanding of hadron reaction theory was achieved and various methods for data analysis and interpretation were proposed [51–53].

S-matrix theory aims at the construction of amplitudes based on the principles of analyticity, unitarity and crossing symmetry. Bound states, resonances and thresholds determine singularities. At low energies, meson dynamics is controlled by the nature of chiral symmetry breaking in QCD. In the hadron world, this is encoded in the Lagrangians of Chiral Effective Field Theories, and inputs from these will be embodied in the amplitudes fed into AmpTools. Moreover, Regge theory provides constraints between direct-channel and crossed-channel dynamics. A key feature of modern amplitude analysis is that the parameters of the Chiral Effective Theories at low energies and those of the Regge dynamics at higher energies be simultaneously constrained by input from a database encompassing a wide range of reactions, including not just traditional meson and baryon production, but also the final states in heavy flavor decays, from BaBar, Belle, BESIII and increasingly LHCb. This duality between directly produced resonances and Reggeons, which determine the high-energy reactions, is key in constraining resonance parameters that so far has not been implemented in modern amplitude analysis.

Consider for example the $J^{PC} = 1^{-+}$ isospin-1 exotic meson. The lowest mass two body channels that it can couple to are the P-wave, $\eta^{(')}\pi$. According to duality arguments, a resonance in the direct,

s-channel should be dual to the t and u channel reggeon exchanges, which in this case are dominated by the f and the a meson trajectories. To a good approximation, these trajectories are exchange degenerate, thus the s-channel is expected to be dominated by even partial waves. This is consistent with the exotic P-wave not been dual to normal mesons. Given the expected gluon content of the hybrid mesons t is possible, however, that the exotic is is instead dual to subleading trajectories involving Regge-Pomeron cuts.

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