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Modern hadron spectroscopy: a bridge between nuclear and particle physics.

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Abstract. In this talk I discuss aspects of hadron physics, which soon are expected to shed new light on the fundamental QCD phenomena. In the analysis of hadron reactions and their properties I emphasize similarities to the nuclear many body problem.

1. Introduction

The vast majority of nuclear phenomena can be understood using protons and neutrons as elementary constituents and the nonrelativistic interactions among them. On the other hand, Quantum Chromodynamics (QCD), which is the underlying theory of nuclear forces, describes the relativistic quarks and gluons as the fundamental degrees of freedom. It is fascinating that the behavior and properties of the "elementary" hadrons, *i.e.* isolated bound states of quarks and gluons share many similarities with both, the low-energy nuclear phenomena as well as the high-energy QCD behavior.

2. Hadrons as a window for novel QCD phenomena

Confinement is the distinguishing feature of QCD [1]. 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. Confinement is due to self-interactions between gluons, which are the mediators of the strong force between colored quarks and other gluons. The light, *u* and *d* quarks that make up the nuclei are $O(100)$ times lighter than the proton and thus the relativistic interactions between gluons are in fact responsible for the bulk of the visible mass in the Universe. The same gluons that provide binding between quarks and produce the nucleon mass can also be active in the hadron spectrum. However, since gluons carry no charge other than color, gluons are invisible to external probes. For these reason, gluons remain the most mysterious particles of the Standard Model. Fortunately, their contribution to the hadron spectrum is expected to produce novel states of matter [2] and new experimental programs have just began searching for such matter, which is dominated by radiation and referred to as glueballs and hybrids. The latter contains both quarks and excited gluons.

Hadrons are the "simplest" bound states of quarks and gluons allowed by confinement and studies of individual hadrons and their interaction offer a unique window into this fundamental



phenomenon. 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 and LHCb at CERN, RHIC in the US, VES in Russia, Belle in Japan and JLab in the US. PANDA in Germany, is in the construction phase, and future facilities under discussion include the Electron Ion Collider in the US. The new experiments at these facilities generate complicated data sets, which demand a qualitatively new level of sophistication in analysis never before achieved [3]. In particular development of theoretical, phenomenological and computational underpinning of data analysis and interpretation is urgently needed to take full advantage of the information contained in the experimental data.

Since the early days of the hadron physics research, the quark model has provided the main template for "constructing" hadrons [4]. Over the years sophisticated extensions of the quark "shell model" of hadrons have been proposed [5, 6, 7, 8, 9]. While very successful in providing important insights into the nature of hadron interactions and their properties, such as the magnetic moment and charge distributions, the precise rooting of the quark model in QCD remains unsolved. In recent years, lattice gauge simulations have enabled first principle, numerical studies of QCD [10]. As a result, new insights into the hadron resonance spectrum have emerged. These have largely confirmed the naive quark model expectations that attributes the existence of the lightest hadrons to binding of quark-antiquark pairs for mesons and three quarks for baryons. The key question is how the almost massless quarks which, can in principle be copiously produced from gluon fusion become massive and that only a few of them are needed to build a hadron. A possible mechanism based on the mean field approximation borrows from the techniques of Hartee-Fock-Bogolubov used in condensed matter and nuclear physics. In the QCD vacuum the Fermi-Dirac sea becomes perturbed when an external quark-antiquark are inserted and a condensate is formed. An excitation of this condensate, which is similar to a spin wave in a magnetic material can be identified with pions, which are the lightest of mesons [11]. The external quarks, because of the long range long range, confining interaction between their color charges and those of the individual quark in the medium acquire an effective mass. The mass is, however, finite and of the order of a few hundred MeV, because of the color neutrality of the vacuum. A similar mass generation mechanisms can apply to gluons. The main complication here arises from the strong gauge dependence. What a gluon is strongly depends on the choice of gauge. As it is in the case of nonrelativistic QED, QCD in the Coulomb gauge provides with the canonical relation between gluons as particles and gluons as fields. Unfortunately, QCD in the Coulomb gauge is highly nonlinear, which limits the reach of analytical approaches [12, 13]. From the numerical, lattice gauge simulations, it appears that gluons in the vacuum form complicated topological structures of monopoles and vortices [14]. In a popular confinement scenario, the condensate of chromo-magnetic monopoles screens the chromo-electric field emerging from the color charges of quarks and gluons, which instead of spreading out in a Coulomb-like pattern become collimated into flux tubes. This phenomenon is referred to as the dual Meissner effect (in the normal Meissner effect, in electric superconductor magnetic fields are screened by the freely moving electric charges). When this picture is considered in the Coulomb gauge, where besides the gluon condensate there are physical, particle-like gluons one finds that the latter, because of the interactions with the condensate behave effectively as massive axial vector particles, *i.e* with spin (J), parity (P) and charge conjugation (C) quantum numbers of $J^{PC} = 1^{+-}$ [15, 16]. When such a quasi-gluon is combined with a quark antiquark pair, that has quantum numbers of $J^{PC} = 0^{-+}$ in the spin zero state and 1^{--} in the spin-one state one obtains four states with the J^{PC} quantum numbers, 1^{--} and $(0, 1, 2)^{-+}$ [17]. These states are interpreted describing the four lightest hybrids mesons, that include the so called exotic hybrid, which is the one with $J^{PC} = 1^{-+}$. It is exotic, because unlike the other combination of the J , P and C quantum numbers, the exotic

combination cannot be obtained from combining quark and antiquark quantum numbers alone. Therefore, a resonance with exotic quantum numbers is being extensively searched for a smoking gun indication of gluon excitation in the hadron spectrum. The pattern of hybrid mesons that emerge in Coulomb gauge has recently been confirmed by lattice simulations [18]

Identification of exotic hadrons in the spectrum requires sophisticated methods of partial wave and reaction amplitude analysis. This is because in the mass region where the new hadrons are expected there are several open channels that contribute to the non-resonance backgrounds complicating extraction of the signal. When treated as complex functions of the kinematical variables, reaction amplitudes have singularities that originate from presence of resonances. Thus, to properly extract resonance parameters it is necessary to develop analytical reaction amplitudes.

Several new experiments at the Jefferson Lab that began operation this year will be searching for the hybrid meson and baryon resonances. The experiments use the 12 GeV photon beam from the energy upgraded CEBAF accelerator that are scattered peripherally on the hydrogen target (for meson resonance extraction) or centrally, for studies of the baryon spectrum. In case of (point-like) photon-induced reactions kinematical separation of the beam and target fragmentation is highly nontrivial and requires deep understanding of the underlying production process. For example, microscopically, the peripheral photo-production involves scattering of photons on the virtual meson cloud surrounding the proton target and should be described with the framework of the Regge theory. A particularly interesting aspect of this reaction involves production of the lightest pions [19, 20]. Specifically, through studies of the photon polarization asymmetries, one can isolate production via exchange of natural (ρ, ω) vs unnatural parity (b, h) reggeons. Recent theoretical predictions by the JPAC collaboration indicating dominance of the natural component have been confirmed by the first measurement performed with GlueX detector [21]. Confirmation of the theoretical production models by these early measurements opens path for rigorous analysis of the data and potential discovery of the new QCD phenomena associated with gluon excitations.

3. Summary

New advancements in experimental techniques, numerical and analytical approaches to QCD are expected to provide key insights into the fundamental aspects of QCD, such as confinement and mass generation. These advancements will help to further integrate the hadron and nuclear physics manifestations of the strong interactions.

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References

- [1] Gross D in *Proceedings of the 2000 International Superstrings Conference University of Michigan, Ann Arbor*.
- [2] Briceno R A *et al.* 2016 *Chin. Phys. C* **40** 042001
- [3] Battaglieri M *et al.* 2015 *Acta Phys. Polon. B* **46** 257
- [4] Shepherd M R, Dudek J J and Mitchell R E 2016 *Nature* **534** 487
- [5] Godfrey S and Isgur N 1985 *Phys. Rev. D* **32** 189
- [6] Capstick S and Isgur N *Phys. Rev. D* **34** 2809
- [7] Roberts C D and Williams A G 1994 *Prog. Part. Nucl. Phys.* **33** 477
- [8] Bijker R and E. Santopinto E 2009 *Phys. Rev. C* **80** 065210
- [9] Eichmann G *et al.* 2016 *Prog. Part. Nucl. Phys.* **91** 1
- [10] Briceno R A, Dudek J J and Young R D arXiv:1706.06223 [hep-lat].
- [11] Szczepaniak A P and Swanson E S 2001 *Phys. Rev. Lett.* **87** 072001
- [12] Christ N H and Lee T D *Phys. Rev. D* **22** 939
- [13] Gribov V N 1978 *Nucl. Phys. B* **139** 1

- [14] Greensite J 2003 *Prog. Part. Nucl. Phys.* **51** 1
- [15] Szczepaniak A P and Krupinski P 2006 *Phys. Rev. D* **73** 116002
- [16] Guo P, Szczepaniak A P, Galata G, Vassallo A and Santopinto E 2008 *Phys. Rev. D* **77** 056005
- [17] Guo P, Szczepaniak A P, Galata G, Vassallo A and Santopinto E 2008 *Phys. Rev. D* **78** 056003
- [18] Dudek J J, Edwards R G, Peardon M J, Richards D G and Thomas C E 2010 *Phys. Rev. D* **82** 034508
- [19] Mathieu V *et al.* 2017 *Phys. Lett. B* **774** 362
- [20] Nys J *et al.* [JPAC Collaboration], arXiv:1710.09394 [hep-ph].
- [21] Ghoul H Al *et al.* [GlueX Collaboration] 2017 *Phys. Rev. C* **95** 042201