MULTIQUARK HADRONS

This work summarizes the salient features of current and planned experiments into multiquark hadrons, describing various inroads to accommodate them within a theoretical framework. At a pedagogical level, authors review the salient aspects of Quantum Chromodynamics (QCD), the theory of strong interactions, which has been brought to the fore by high-energy physics experiments over recent decades. Compact diquarks as building blocks of a new spectroscopy are presented and confronted with alternative explanations of the *XYZ* resonances. Ways to distinguish among theoretical alternatives are illustrated, to be tested with the help of high-luminosity LHC, electron-positron colliders, and the proposed Tera-Z colliders. Non-perturbative treatments of multiquark hadrons, such as large N expansion, lattice QCD simulations, and predictions about doubly heavy multiquarks are reviewed in considerable detail. With a broad appeal across high-energy physics, this work is pertinent to researchers focused on experiments, phenomenology or lattice QCD.

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Preface

Multiquark physics started essentially with the discovery of $X(3872)$ in 2003 by the Belle collaboration at the KEK-B factory. It profited greatly from the high-luminosity particle accelerators: the e^+e^- B factories and BEPC, and the hadron colliders Tevatron and LHC.

Well over a dozen exotic mesons, and two charged baryons, which do not fit in the quark model, have been observed. They are called XYZ mesons and P_c baryons. Some of these exotic mesons, such as $Z(3900)$ and $Z_b(10650)$, decaying into $J/\psi\pi^\pm$ and $\Upsilon(1S)\pi^\pm$, respectively, have a minimum of four quarks in the valence approximation. They are generically called tetraquarks. Likewise, the two exotic charged baryons, $P_c(4380)$ and $P_c(4450)$, whose discovery mode is $J/\psi p$, require a minimum of five valence quarks, and are called pentaquarks. They have received, and continue to receive, a lot of experimental and theoretical attention. It is fair to say that multiquark physics has moved from its exploratory, and at times contentious, stage to the mainstream of hadronic physics.

This book summarizes the main results in this field. We intended to focus on the experimental discoveries, which serve as milestones, and hence are highlighted in a number of chapters. The bulk, however, is an attempt to describe the main theoretical ideas and the methods, which have been used to understand the underlying dynamics. This is still very much a work in progress, as quantitative results from lattice QCD (Quantum Chromodynamics), the reliable workhorse of particle physics , are still lacking due to the complex nature of multiquark hadrons. Consequently, at present there is no theoretical consensus on the templates used in constructing these hadrons. In the absence of first principle calculations, various approximate schemes and phenomenological approaches have been adopted. Some of these methods are borrowed from nuclear physics, and treat the exotic hadrons as hadronic molecules, in which the pion- and other light-meson-exchanges play a fundamental role. Some others are inspired by the phenomenologically successful constituent quark model, in which diquarks, having well-defined color and spin-parity quantum numbers, are introduced, in addition to quarks, with the dynamics governed by the spin-spin interactions embedded in QCD. These models have been subjected to respect the well-established heavy-quark and chiral symmetries of QCD. An important aid in establishing firmly the multiquark states, tetraquarks and pentaquarks, and in studying their decays is played by the QCD methods in the large-N limit (N being the number of colors). A chapter is devoted in the book to illustrate this.

Light scalar mesons, such as σ, κ, f_0, and a_0, have been put forward as candidates for tetraquark states. Their case rests on the inverted mass hierarchy in the isospin-mass plots, compared to the well-known pseudoscalar and vector mesons, which all fit in as quark-antiquark bound states. Being low in mass, they are also sensitive to the infrared sector of QCD, in which instantons play an important role. We discuss this in a chapter in this book.

Apart from the light scalars, the other candidate tetraquark and pentaquark states observed so far have a common thread which runs through all of them, namely they have a hidden heavy quark-antiquark pair, charm-anticharm, $c\bar{c}$, or beauty-antibeauty, $b\bar{b}$, in their Fock space. It seems that heavy quarks (and antiquarks) are essential in discovering deeper structures in QCD. This is a recurrent theme of this book and illustrated in a number of cases of interest, culminating in the predictions of doubly heavy tetraquarks, such as $bb\bar{u}\bar{d}$ and $bb\bar{u}\bar{s}$, which are widely anticipated to be stable under strong interactions.

In our opinion, a new chapter of QCD has opened up in the form of a second layer of hadrons, beneath the well-established quark-antiquark mesons and the three-quark baryons. If this view is tenable, then we anticipate a very rich spectroscopy of multiquark hadrons, which we outline using the diquark model as a guide. Clearly, a lot of this remains to be tested experimentally. Depending on the outcome of these experiments, some of the theoretical schemes may have to be modified, or even abandoned. The book aims at pointing out these crucial measurements and in stimulating a theoretical discourse, enabling in turn to achieve a consensus. However, it is not intended to be either a comprehensive review or a text book. For that, we would have been forced to enlarge its size far beyond the 200-page length that we intended to write. We do provide a bibliography which is detailed enough to follow up on some of the topics in which the readers may be interested for further details. We hope that as a research monograph on an emerging field, this book will stimulate the new entrants to this field, triggering new ideas and in developing quantitative techniques, such as lattice QCD.

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