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Review

Nuclear-bound quarkonia and heavy-flavor hadrons

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ABSTRACT

In our quest to win a deeper understanding of how QCD actually works, the study of the binding of heavy quarkonia and heavy-flavor hadrons to atomic nuclei offers enormous promise. Modern experimental facilities such as FAIR, Jefferson Lab at 12 GeV and J-PARC offer exciting new experimental opportunities to study such systems. These experimental advances are complemented by new theoretical approaches and predictions, which will both guide these experimental efforts and be informed and improved by them. This review will outline the main theoretical approaches, beginning with QCD itself, summarize recent theoretical predictions and relate them both to past experiments and those from which we may expect results in the near future.

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1. Introduction

There is now overwhelming evidence that Quantum Chromodynamics (QCD) is indeed the fundamental theory of the strong interaction and yet we are very far from actually understanding how it works. Certainly lattice QCD has had remarkable success with ground state hadrons, mesons with a simple quark–anti-quark pair and baryons with three valence quarks [1]. Yet beyond that our ignorance is profound. After decades of speculation about, and searches for, colorless states with more than the minimal number of valence quarks we still have no idea whether such states exist or indeed whether QCD predicts them or not.

In the list of particles that have come and gone at various times we think of dibaryons [2–4], pentaquarks [5,6] and exotic mesons [7]. Certainly, in the study of excited baryons it has recently become clear that the $\Lambda(1405)$ is an anti-kaon–nucleon bound state [8] and that the Roper resonance is almost certainly dynamically generated through meson–baryon coupled channel dynamics [9], although there is no consensus on this [10]. There is now a zoo of excited states of the $c\bar{c}$ system that must involve more than a simple quark–anti-quark pair. Yet there is no consensus as to whether these are molecular states, threshold effects or genuine exotic states bound by gluonic forces. Until we can find definitive answers to such issues, it is not possible to classify our understanding of QCD as more than superficial.

The study of the interactions of quarkonia with atomic nuclei is an extremely promising avenue for exploring such issues. Because of the Zweig rule, the mean fields generated by light meson exchange, which provide a natural explanation of the binding of atomic nuclei, cannot bind a $c\bar{c}$ or $b\bar{b}$ pair and *if* such states are indeed bound to nuclei one must look to other mechanisms, including gluon exchange.

Thus the key issues in this field are firstly whether quarkonia are indeed bound to nuclei, secondly by how much and what are the properties of such states and thirdly how can one quantitatively understand these observations in terms of QCD. This work aims to summarize the status of the theoretical and experimental work in this exciting area. It is complementary in some aspects to the recent review by A. Hosaka et al. in Ref. [11]; while the main focus of the latter is on properties of heavy hadrons in nuclear matter and few-body systems, the present review focuses on nuclear binding phenomena of quarkonia and heavy-flavor hadrons that are of direct relevance for the experiments planned at existing and forthcoming facilities that include FAIR, Jefferson Lab at 12 GeV and J-PARC. Ref. [12] is an experimental review focusing on light-meson nuclear potentials, with a section dedicated to charmed nuclei.

The review begins with a reminder, in Section 2, of QCD and especially its adaptation to heavy quark systems, with an emphasis on non-relativistic QCD, NRQCD, which has proven very successful in dealing with heavy quark systems. This is followed by a discussion of potential NRQCD, pNRQCD, which combines NRQCD with effective field theory to yield a Hamiltonian describing the gluon-mediated interactions of quarkonia with other colorless systems.

Section 3 is an outline of the quark–meson coupling (QMC) model. This model starts at the level of the quark structure of hadrons, focusing on the interactions between them mediated by meson exchange, including the change of the internal structure of a hadron immersed in a nuclear medium implied by the self-consistent solution of the field equations. The QMC model serves as a natural way to calculate the non-gluonic mechanisms which may contribute to the binding of quarkonia.

Section 4 deals with the ideal case of the interactions of the J/Ψ with nuclei. In terms of QCD this may be viewed as a small color dipole immersed in a nuclear medium and so goes to the heart of the issue elaborated earlier, namely how QCD actually works in systems with more than the smallest number of valence quarks. While the J/Ψ presents particular challenges because of its larger mass, any nuclear levels should be quite narrow and this should make their experimental identification, once formed, quite straightforward.

Although in the context of this review the strange quark is not particularly heavy, because the ϕ meson is almost entirely $s\bar{s}$, with little light quark content, it serves as a promising way to access the physics at the heart of this review. In Section 5 we outline the many experiments which have already given some hints of binding of the ϕ to atomic nuclei as well as the more modern attempts in preparation. This experimental work is carefully placed in the context of modern theoretical expectations.

Although they are not strictly quarkonia, there has recently been quite a bit of experimental interest in the possible binding of η, η' and ω mesons and we devote Section 6 to this topic. Section 7 deals with the natural extension of heavy flavored hadrons, D, $\overline{D}$ mesons and hypernuclei, namely bound states of D, $\overline{D}$ mesons as well as Λ_c^+ and Λ_b baryons to nuclei. Finally, Section 8 contains some concluding remarks.