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Heavy quark meson spectroscopy: Experimental results and perspectives

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Abstract. In this paper I will present a brief experimental overview of the Heavy Quark Meson Spectroscopy, with particular emphasis on charmonium, bottomonium and open charm mesons, as well as the new states above threshold (the so-called XYZ states).

1. Introduction

One of the most challenging and fascinating goals of modern physics is the achievement of a fully quantitative understanding of the strong interaction, which is the subject of hadron physics. Significant progress has been made over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated a very intense theoretical activity and a refinement of the theoretical tools. Still there are many fundamental questions that remain basically unanswered. Phenomena such as the confinement of quarks, the existence of glueballs and hybrids, the origin of the masses of hadrons in the context of the breaking of chiral symmetry are long-standing puzzles and present the intellectual challenges in our attempt to understand the nature of the strong interaction and of hadronic matter. Hadron spectroscopy is one if the key experimental studies that will help us understand these fundamental questions.

1.1 The strong interaction and QCD

The modern theory of strong interactions is Quantum Chromodynamics (QCD), a quantum field theory of quarks and gluons based on the non-Abelian gauge group SU(3). It is part of the Standard Model of particle physics. QCD is well tested at high energies, where the strong coupling constant α_s is small and perturbation theory applies. In the low-energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood. Some of the central questions are: How can we bring order into the rich and complex phenomena of low-energy QCD? Are there effective degrees of freedom in terms of which we can understand the resonances and bound states of QCD efficiently and systematically? Does QCD generate exotic structures so far undiscovered?

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In order to deal with QCD in the non-perturbative regime, various theoretical frameworks have been developed, of which the best established are Lattice QCD (LQCD) and Effective Field Theories (EFT) [1].

Lattice QCD is an *ab initio* approach, in which the QCD equations of motion are discretized on a 4-dimensional space-time lattice and solved by means of large-scale numerical simulations on big computers. Over the past few years, LQCD has made enormous progress (e.g. gradual transition from quenched to unquenched calculations) and, thanks also to synergies with EFT (discussed below), many impressive results have been obtained with ever increasing precision.

Effective Field Theories exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective Lagrangians that are equivalent to QCD for the problem at hand. We distinguish between EFT formulated in terms of quark-gluon degrees of freedom (e.g. Non-Relativistic QCD, NRQCD) and in terms of hadronic degrees of freedom (e.g. Chiral Perturbation Theory).

An additional framework within which non-perturbative problems are sometimes dealt with, even though not always rigorously justified in QCD, is represented by **potential models**. In this approach, bound systems of heavy quarks are treated in terms of non-relativistic potentials with forms that reproduce the asymptotic behaviours of QCD. Masses and widths of the bound states are obtained by solving Schrodingers equation and can then be compared with experiment.

1.2 Experimental study of hadron physics

In order to answer the open questions, dedicated experiments that test QCD in the non-perturbative regime and improve our limited understanding of these aspects of QCD are crucial. These measurements include the spectroscopy of QCD bound states, the search of new forms of hadronic matter, the study of nucleon structure and many more.

Experimentally studies of hadron physics can be performed with different probes such as electrons, pions, kaons, protons or antiprotons. However the two main environments in which these studies have been carried out are e^+e^- and $\overline{p}p$ annihilation.

In e^+e^- annihilation, direct formation proceeds through an intermediate virtual photon and is therefore limited to the vector states (JPC = 1–). Other production mechanisms include photon-photon fusion, initial state radiation and B-meson decay. e+e- annihilation is characterized by low hadronic background and high discovery potential. The main disadvantage is that, as mentioned above, direct formation is limited to the vector states and this implies a limited mass and width resolution for the non-vector states.

In $\overline{p}p$ annihilation, thanks to the coherent annihilation of the three quarks in the proton with the three antiquarks in the antiproton, it is possible to form directly states with any (non-exotic) quantum number combination via intermediate states with the appropriate number of gluons. This makes it possible to achieve an excellent mass and width resolution for all states. $\overline{p}p$ annihilation is also characterized by a high discovery potential, but with a hadronic background that is higher than in e^+e^-. Exotic states can be produced in $\overline{p}p$ annihilation.

2. Heavy quarkonium

The study of heavy quarkonium, i.e. the bound state of a heavy (c or b quark) and its antiquark, provides a powerful tool for the understanding of the strong interaction. The high quark mass makes it plausible to attempt a description of the dynamical properties of the $\overline{Q}Q$ system in terms of non relativistic potential models, in which the functional form of the potential is chosen to reproduce the asymptotic properties of the strong interaction. The free parameters in these models are to be determined from a comparison with the experimental data.

Now, more than thirty years after its discovery, heavy quarkonium continues to be an exciting and interesting field of research. The recent discoveries of new states, some of which expected ($\eta_c(2S)$, h_c, η_b, h_b, ...) and some totally unexpected ($X(3872)$ and all the new X, Y, Z states, have given rise to renewed interest in heavy quarkonium and stimulated a lot of experimental and theoretical activities.

The gross features of the spectra are reasonably well described by potential models, but these obviously do not tell the whole story: relativistic corrections are important (especially for charmonium), and other effects, such as coupled-channel effects, are significant and can considerably affect the properties of the $\overline{Q}Q$ states. To explain the finer features of the heavy quarkonium system, model calculations and predictions are made within various, complementary theoretical frameworks. Substantial progress in an effective field theoretical approach, called Non Relativistic QCD (NRQCD), has been achieved in recent years. This analytical approach makes it possible to expect significant progress in LQCD calculations, which have become increasingly more capable of dealing quantitatively with non-perturbative dynamics in all its aspects, starting from the first principles of QCD.

In the following I will report some recent results in charmonium and bottomonium spectroscopy, whereas the discussion of the new states above open charm threshold will be the subject of Sect. 3.

2.1 Recent results in charmonium spectroscopy

All 8 states below the open charm threshold have been observed experimentally and their main properties have been measured. The two most recent discoveries are the $\eta_c(2S)$ and the h_c.

The $\eta_c(2S)$ was discovered by the Belle collaboration [2] in the hadronic decays of the B meson $B \to K + \eta_c(2S) \to K + K_s K^- \pi^+$ and subsequently confirmed by CLEO [3] and BaBar [4], which observed this state in two-photon fusion. The PDG [5] value of the mass is $3638.9 \pm 1.3\,\mathrm{MeV/c^2}$, corresponding to a surprisingly small hyperfine splitting of $47.2 \pm 1.3\,\mathrm{MeV/c^2}$, whereas the total width is only measured with an accuracy of 40%. The BES III collaboration has recently reported evidence for the decay $\eta_c(2S) \to K_s K^\pm \pi^\mp \pi^+ \pi^-$ [6], yielding a mass and total width in agreement with previous measurements.

The $h_c(1P)$ is of particular importance in the determination of the spin-dependent component of the $c\bar{c}$ potential. In the non-relativistic potential model description the central potential is generally written as the sum of a Coulomb term with vector Lorentz structure (arising from one-gluon exchange) plus a confining term with scalar Lorentz structure [7]. For such a potential, the hyperfine splitting between spin-singlet and spin-triplet P-wave is very small (or vanishing). A significant deviation from this expectation could be evidence of an unexpected Lorentz structure, or for the existence of new effects, which are not included in non-relativistic potential model calculations. The h_c was observed by CLEO in the process $e^+e^- \to \psi(2S) \to h_c\pi^0$ [8], with $h_c \to \eta_c + \gamma$, in which the η_c was identified via its hadronic decays. Recently the BES III collaboration reported a very nice h_c signal, in which the η_c was reconstructed via 16 hadronic decays [9]. The PDG [5] value for the h_c mass is $3525.38 \pm 0.11\,\mathrm{MeV/c^2}$, corresponding to a hyperfine splitting $\mathrm{M}(^3P) - \mathrm{M}(^1P) = (-0.08 \pm 0.13)\,\mathrm{MeV/c^2}$, where $\mathrm{M}(^3P)$ is the center of gravity of the ^3P_J states. Thus the hyperfine splitting for the P states is consistent with theoretical expectations.

2.2 Recent results in bottomonium spectroscopy

For the bottomonium system ($b\bar{b}$) the agreement between theoretical predictions and experimental findings should be better than for charmonium for several reasons. First of all the b quark is heavier than the c quark, therefore relativistic corrections are less important in bottomonium than in charmonium. Furthermore at this higher energy scale the QCD coupling strength α_s is smaller, which makes perturbative calculations more reliable. Finally, in the energy region of bottomonium the $Q\overline{Q}$ potential is dominated by the Coulomb term, so that uncertainties in the confinement term are less significant.

Even though bottomonium was discovered in 1977, the ground state spin-singlet $\eta_b(1S)$ was found only recently by the BaBar collaboration in the radiative decay of the $\Upsilon(3S)$ [10] and $\Upsilon(2S)$ [11] in the process $e^+e^- \rightarrow \Upsilon \rightarrow \eta_b + \gamma$. The collaboration studied the photon energy spectrum and observed a peak at an energy of $(921.2^{+2.1}_{-2.8})$ MeV, corresponding to an η_b mass of $(9391.1 \pm 3.1)\,\mathrm{MeV/c^2}$, yielding a hyperfine splitting $M(\Upsilon(1S)) - M(\eta_b(1S)) = (69.9 \pm 3.1)\,\mathrm{MeV/c^2}$, in good agreement with LQCD calculations [12], but not with those of the constituent quark model (CMQ) [13]. The observation of the $\eta_b(1S)$ is thus an important validation of LQCD predictions.

The Belle collaboration recently reported the observation of the $h_b(1P)$ and $h_b(2P)$ states of bottomonium [14] produced in the reaction $e^+e^- \rightarrow h_b(nP)\pi^+\pi^-$ using a 121.4 fb^{-1} data sample collected at energies near the $\Upsilon(5S)$. They measured masses $M(h_b(1P)) = (9898.3 \pm 1.1^{+1.0}_{-1.1})\,\mathrm{MeV/c^2}$ and $M(h_b(2P)) = (10259.8 \pm 0.6^{+1.4}_{-1.0})\,\mathrm{MeV/c^2}$, which correspond to P-wave hyperfine splittings of $(1.6 \pm 1.5)\ \mathrm{MeV/c^2}$ and $(0.5^{+1.6}_{-1.2})\,\mathrm{MeV/c^2}$, respectively. These hyperfine splittings are consistent with zero and in agreement with theoretical expectations. The $h_b(1P)$ and $h_b(2P)$ are observed with significances of 5.5σ and 11.2σ, respectively.

The BaBar collaboration had previously reported the results of a search for the $h_b(1P)$, performed using 122 million $\Upsilon(3S)$ events in the decay: $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$, with $h_b(1P) \rightarrow \gamma\eta_b(1S)$ [15]. The experiment observed an excess of events above background in the distribution of the recoil mass against the π^0 at mass $(9902pm4 \pm 2)\,\mathrm{MeV/c^2}$. The width of the observed signal is consistent with experimental resolution and its significance is 3.1σ. The resulting hypefine splitting with respect to the center of gravity of the $\chi_b(1P)$ states is $(2 \pm 4 \pm 2)$ MeV, consistent with zero and with model predictions [16, 17]. The mass values for the $h_b(1P)$ measured by BaBar and Belle are in good agreement with each other.

3. New states above threshold (X, Y, Z states)

The energy region above the $D\overline{D}$ threshold is rich in interesting new physics. In this region one expects to find the D-wave states. Of these only the 1^3D_1, identified with the $\psi(3770)$ resonance, has been found. The $J = 2$ states (1^2D_2 and 1^3D_2) are predicted to be narrow, because parity conservation forbids their decay to $D\overline{D}$. In addition to the D states, the radial excitations of the S and P states are predicted to occur above the open charm threshold. None of these states have been positively identified, with the possible exception of the $\chi_{c2}(2P)$, which has been observed with a mass of approximately $3930\,\mathrm{MeV/c^2}$ (formerly known as the $Z(3930)$) [27, 28].

On the other hand a number of new states have recently been found at the B-factories (and confirmed by other e^+e^- machines and at the Fermilab Tevatron) whose nature is not yet understood. These states, which are produced through many different mechanisms (such as B-meson decay, Initial State Radiation (ISR), photon-photon fusion, double-charmonium), are usually associated with charmonium because they decay predominantly into charmonium states (such as the J/ψ or the $\psi(2S)$) and $D\overline{D}$, but their interpretation is far from obvious. In fact, some of them might be some previously unobserved form of hadronic matter, such as molecules, multiquark states or even charmonium hybrids. It is therefore understandable that these discoveries have stimulated a lot of theoretical and experimental activity and that they have played a significant role in determining a true renaissance of hadron physics. More than twenty such states have been discovered over the past 11 years. In the following I will briefly discuss the $X(3872)$, the $Y(4260)$ and the $Z^{\pm}(3900)$.

The first of these states to be discovered, and by far the best studied, is the $X(3872)$: first observed by Belle [29] in the hadronic decay of the B meson it was subsequently confirmed at BaBar, CDF, D0, LHCB and BESIII. Its main features are a very small width ($\Gamma < 1.2$ MeV), a mass which is very close to the D^0D^{0*} threshold and quantum numbers $J^{PC} = 1{+}{+}$, which suggest that this state might be a molecular or tetraquark state, although other interpretations are still possible.

The $Y(4260)$ was discovered by BaBar using the ISR technique [30] and subsequently observed by CLEO, Belle and BES III. Its production mechanism fixes the quantum numbers to be $J^{PC} = 1^{--}$. It is a wide state ($\Gamma = 108 \pm 12\,\mathrm{MeV}$) with a mass of $4250 \pm 9\,\mathrm{MeV/c^2}$ [5]. The absence of an available vector slot in the charmonium spectrum together with the absence of open charm decays seems to indicate that this is not a conventional $c\bar{c}$ state. One of the hypotheses being considered is that of a charmonium hybrid.

Perhaps the most intriguing states discovered in the past few years are the charged states: after the controversial $X(4430)$ observed by Belle [31, 32] but not by BaBar [33] three more states have been discovered by the BES III collaboration. Of these the $Z^{\pm}(3900)$ [34] has also been confirmed by Belle [35] and by an analysis of the CLEOc data [36]. This state is observed through its decay to $\pi^{\pm} J/\psi$, thus its minimal quark content is $u\bar{d}c\bar{c}$, an indication of its exotic nature.

4. Open charm mesons

Open charm mesons, consisting of a heavy and a light constituent, are very interesting objects for the understanding of the strong interaction, since they combine the aspect of the heavy quark as a static colour source on one side and the aspect of chiral symmetry breaking and restoration due to the presence of the light quark on the other side. Based on earlier observations of low-lying D meson states, the phenomenological quark model was thought to be able to provide an accurate description of the excitation spectra of heavy-light systems. The experimentally observed spectrum of non-strange D mesons [18] was consistent with the expected pattern of states (although for some of the states the spin-parity assignment could not be given) and it was believed that the same model could predict also the unobserved D meson states with reasonable precision. The situation changed drastically over the past nine years, with a series of unexpected discoveries of new states which did not fit in the quark model predictions. The first state to be discovered was the narrow $D_s(2317)$, which was observed in e^+e^- annihilation by BaBar in the decay mode $D_s + \pi^0$ [19] and shortly afterwards confirmed by CLEO [20] and Belle [21]. At the same time CLEO found a new, narrow state $D_s(2460)$ [20] decaying to $D_s^* + \pi^0$. This state was subsequently confirmed by Belle [21] and BaBar [22, 23]. The width of both states is small, since the $D_s(2317)$ lies below the DK threshold (hence it cannot decay by kaon emission), and the $D_s(2460)$ lies below the D^*K threshold and, with $J^P = 1^+$, it cannot decay by kaon emission either. The situation became even more complicated when BaBar discovered the $D_{sJ}(2860)$ decaying to D^0K^+ and D^+K_S [24], Belle discovered the $D_{sJ}(2710)$ decaying to D^0K^+ [25], and BaBar found a new, broad state $D_{sJ}(3040)$ [26]. These unexpected discoveries attracted much interest in the hadron physics community, since the new states do not fit into the quark model predictions for heavy-light systems, in contrast to the previously known D meson states. A lot of theoretical activity is going on trying to understand the nature of these newly discovered mesons.

5. Conclusions and outlook

Hadron physics continues to be an exciting field of research and, over the next few years, many experimental facilities will produce first-rate results: the BES III experiment at the Beijing Electron-Positron Collider, the LHC experiments and COMPASS at CERN, the Belle II experiment at Super KEKB, GlueX and CLAS12 at Jefferson Lab and, towards the end of the decade, the PANDA experiment at FAIR.

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