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Experimental review of charmonium spectroscopy

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Abstract. Charmonium spectroscopy is one of the best means of making precision study of QCD, the strong-interaction component of the Standard Model of particle physics. Recent progress in the study of charmonium, the need for additional precision data, and the opportunities that the new facilities offer, are discussed.

PACS. 12.38.Qk Quantum chromodynamics: Experimental tests – 12.39.Pn Potential models – 13.25.Gv Decays of J/ψ, Υ, and other quarkonia – 14.40.Gx Mesons with $S = C = B = 0$, mass $> 2.5\,\mathrm{GeV}$ (including quarkonia)

1 Introduction

The strong interaction is manifest in Nature through the existence of nuclei, but its foundations lie in the interactions between quarks and gluons as described by the non-Abelian field theory of QCD (Quantum Chromodynamics). The basic properties and symmetries of the interaction are best studied not in the many-body systems that nuclei represent, but in the simplest structures to which it gives rise. Mesons, composed of a quark and an antiquark, constitute such "simple" two-body systems. Further simplification results in Quarkonia in which the quark and antiquark are of the same flavor. Because the masses of the light $SU(3)$ quarks, the up-, down-, and strange-quarks, are very similar (3.3(17) MeV, 7(2) MeV, and 118(38) MeV, respectively [1]), light quark mesons are invariably mixtures of all three flavors. This results in complicated structures and a high density of broad overlapping states. For example, in the 1000 MeV mass region, from 1500 MeV to 2500 MeV, as many as 77 mesons are expected [2] with typical widths of 200–400 MeV. Further, the small masses of the u-, d-, and s-quarks pose serious theoretical problems; the quarks are highly relativistic in these light mesons, and the strong interaction coupling constant is too large to allow the use of perturbation theory.

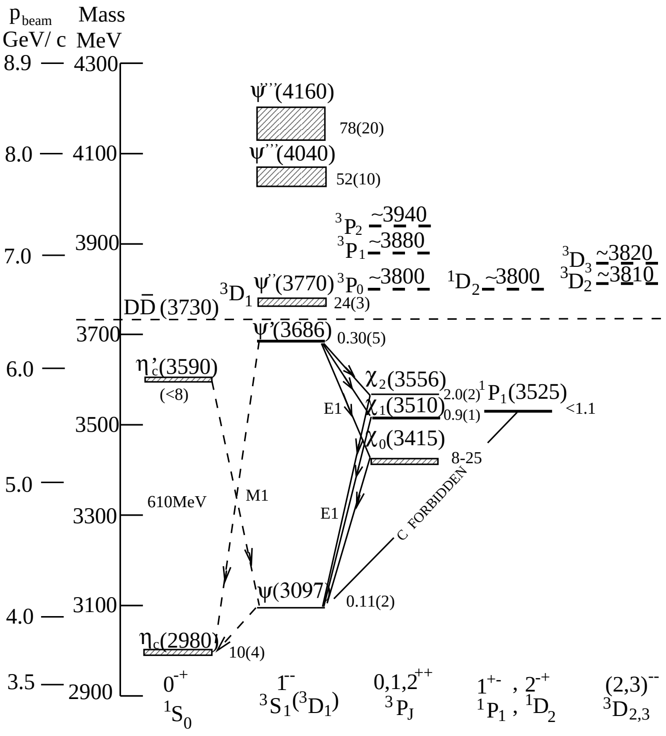

Fig. 1. The charmonium spectrum.

In contrast, the charm quark is much heavier (1260(240) MeV [1]), and relativistic and coupling constant problems in charmonium mesons are much less serious. Figure 1 illustrates the spectrum of charmonium states. Only eight well-isolated and narrow (all widths $\leq 20\,\mathrm{MeV}$) bound states exist in the 800 MeV region from 2900 MeV to 3700 MeV. Thus, the charmonium system is obviously immensely "cleaner" and more tractable than light quark mesons. It offers the best opportunity to make precision spectroscopy of a quarkonium system, and to thus contribute to a deeper understanding of QCD and the phenomenological models based on QCD.

In my talk I reviewed the latest experimental data in charmonium spectroscopy, and the successes and failures

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of the existing experiments, the applicability and limitations of pQCD, the future developments, both theoretical and experimental, which are needed, and the prospects of their realization at upcoming new facilities. It is not possible to present all that in the limited space here. So, the following presentation is essentially a summary of my talk.

2 The experimental developments

As is well known, extensive amount of charmonium spectroscopy was done during 1974-1985 at SLAC with its Mark I, II, III, and Crystal Ball detectors, at Orsay by the DM2 detector, and at DESY by the DASP detector. A large amount of discovery physics was done, but much of it lacked precision. The primary reason for the shortcomings of these experiments was the fact that in these e^+e^- annihilation experiments only the vector states, J/ψ and ψ' could be directly excited, and all other states had to be studied by their indirect excitation via the radiative decays of J/ψ and ψ'. This lead to serious limitations in the study of P-wave states (1^3P_J, χ_c states) and even the ground state of charmonium, the singlet S-wave state ($1^1S_0, \eta_c$). And then, there was the ultimate limitation imposed by the fact that further studies of charmonium stopped as all these facilities moved on to b-quark physics. Both limitations have been overcome by two recent developments. At Fermilab precision studies of charmonium spectroscopy were initiated by the novel technique of the direct formation of resonances of any J^{PC} in proton antiproton annihilation, and at the Beijing Electron Positron Collider (BEPC), the BES detector was commissioned uniquely for the renewed pursuit of charmonium spectroscopy in e^+e^- annihilation.

The BES detector is essentially identical to the Mark III detector at SLAC, and it needs no introduction. The Fermilab technique is unique, and a brief description is desirable. At the Fermilab antiproton source the circulating beam of stochastically cooled antiprotons (upto 8×10^{11} antiprotons) intersected a hydrogen gas-jet target (of density upto 3×10^{14} atom/cm^3). The annihilation products were detected in a detector of cylindrical geometry whose design was optimized for the detection and identification of electrons, positrons, and photons (unfortunately, with no facility for charged-particle tracking). Unprecedented mass resolution with half-width of 300–600 keV was achieved, and luminosities of $(1-5) \times 10^{31}$ cm^{-2}s^{-1} were routinely used. Excitation curves for individual charmonium resonances were measured by varying the antiproton energy across the resonance. The technique resulted in high precision measurements of resonance masses, and direct and precise measurements of total widths.

3 The new results

The new results obtained by the Fermilab E760/E835 experiments are presented in table 1, together with the earlier results of e^+e^- annihilation experiments, as summarized in the PDG(1990) compilation. We see that in the $p\bar{p}$ experiments many results were improved by upto an order of magnitude. Of special note is the nearly 50% increase in the width of the J/ψ-resonance which has the effect of increasing the earlier estimate of the gluon condensate by a similar amount. The large value of $B(p\bar{p})$ for χ_0 is found to be in dramatic violation of the Hadron Helicity Conservation rule of massless QCD, according to which spin-zero states cannot be populated in $p\bar{p}$ anihilation. For a recent review, see ref. [3].

Table 1. Total and partial widths of charmonium states, as measured by e^+e^- annihilation experiment (PDG 1990) and Fermilab $p\bar{p}$ annihilation experiments E760/E835.

State	Γ_{tot} (MeV)	$\Gamma_{\gamma\gamma}$ (keV)	$B(p\bar{p}) \times 10^{-4}$
η_c PDG	$10.3^{+3.8}_{-3.4}$	8^{+7}_{-5}	10.4 ± 1.9
E760	$23.9^{+12.6}_{-7.1}$	$6.7^{+3.3}_{-2.9}$	
E835	$20.4^{+8.0}_{-7.0}$	$3.8^{+2.2}_{-1.4}$	
J/ψ PDG	0.068 ± 0.010		21.6 ± 1.1
E760	0.099 ± 0.013		$18.2^{+3.1}_{-2.6}$
χ_0 PDG	13.5 ± 5.3	4.0 ± 2.8	< 9
E835	9.8 ± 1.0	< 2.0	$4.1^{+1.6}_{-0.9}$
χ_1 PDG	< 1.3		< 12
E760	0.88 ± 0.13		0.86 ± 0.12
χ_2 PDG	2.8 ± 2.1	2.8 ± 2.0	
E760	1.98 ± 0.18	0.321 ± 0.095	1.00 ± 0.11
E835		0.270 ± 0.059	
h_c E760	< 1.1		
η_c' PDG	< 8.0		
ψ' PDG	0.243 ± 0.043		1.9 ± 0.5
E760	0.306 ± 0.039		$2.61^{+0.39}_{-0.36}$

It is worth noticing that the Fermilab/E760/835 experiments did not succeed in providing very good results for the total width, or the two-photon width of the charmonium ground state, η_c. Neither did they succeed in identifying the singlet resonances η_c' (2^1S_0), and $h_c(1^1P_1)$. They also did not attempt to study charmonium above the $D\bar{D}$ threshold at 3.73 GeV, a region in which several interesting narrow resonances ($^1D_2, ^3D_2, 2^1P_1$, etc.) are predicted to exist. The primary reason for most of these shortcomings was the limited amount of antiproton beam-time which could be made available at a facility whose primary objective was to do Tevatron physics. In addition, the design of the E760/E835 detector precluded the study of charged hadron decays of any of the charmonium resonances.

The BEPC/BES experiments have relatively poor photon detection, but have the advantage of being able to identify charged particles. The results from the first series of BES I experiments based on 8 million J/ψ and 3.7 million ψ', often suffered from inadequate statistics. The latest series of BES II measurements are based on 58 million J/ψ and 14 million ψ'. The results from these measurements are beginning to come out, and they supercede, and in some cases contradict, the earlier results. Notable among these is the fact that in the BES II measurements no evidence is found for the narrow $\xi(2230)$ which was claimed to be a candidate for the 2^{++} tensor glueball on the basis of its "observation" in BES I measurements.

With its ability to study charged-particle decay channels, BES has rightly concentrated on measuring a large number of decay channels of both J/ψ and ψ'. A notable result of these measurements is the so called "ρ-π problem". pQCD predicts that the ratio $B(\psi' \to \text{hadrons})/ B(J/\psi \to \text{hadrons})$ should be equal to the ratio $B(\psi' \to e^+e^-)/ B(J/\psi \to e^+e^-) = 0.12$. It is found that for the decay to ρ-π, and to many other decay channels, the ratio is often orders of magnitude smaller. Although many theoretical speculations about this phenomenon have been offered, it is not clear to me why a prediction for the sum of all hadronic decay channels should be expected to be true for individual decay channels, anyway.

BES results for the indirectly populated charmonium resonances, η_c and the χ_J have been controversial in the past. It remains to be seen how these controversies resolve with the new data from BES II. The improvements due to seven times larger statistics are to be expected, but the dependence of width determinations on experimental energy resolution in the different decay channels will perhaps continue to present problems.

BES has also reported quite detailed measurements of the R-parameter $(\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-))$ in the energy region 2–5 GeV. These measurements have given rise to renewed doubt on the correctness of the present "knowledge" of the vector resonances $(\psi''', \psi'''', \psi''''', \text{etc.})$ in the region above the $D\bar{D}$ threshold at 3.73 GeV.

4 Open problems and future prospects

There are many problems and unanswered questions in charmonium spectroscopy. The pursuit of these will require dedicated facilities both for e^+e^- annihilation and proton antiproton annihilation experiments. Fortunately, two such facilities are indeed planned for the near future. These are CESR-c/CLEO-c at Cornell, in Ithaca (USA), and the antiproton physics facilty at GSI, in Darmstadt (Germany).

The CESR-c/CLEO-c project consists of the conversion of the existing high-energy physics facility at Cornell (bottomonium and B-physics) to what has often been called a Tau-Charm Factory [4]. CESR-c will operate in the 2–5 GeV mass region with e^+e^- luminosities in the range of $(1.5\text{–}4.5) \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, essentially factors 30 to 100 more than what is currently available at BEPC, Beijing. The superb CLEO-c detector is being modified to do charmonium and D-physics in a dedicated fashion. Just to give an idea of what this facility is expected to do, let me mention that in about six months operation it is expected to produce one billion J/ψ, and one billion ψ'. With such prolific production one expects to successfully overcome all the disadvantages inherent in the indirect production of non-vector states of charmonium in e^+e^- annihilation, make precision measurements of the decay branching ratios of all charmonium states, and make extremely sensitive searches of hybrids and glueballs. The facility is expected to be in operation within the next year.

The GSI project [5], which has already passed the initial stages of review, and expects formal approval within the next year, will have an accelerator complex which can store upto 15 GeV/c of cooled antiprotons. With an internal target it will be able to improve and extend the high precision measurements done at Fermilab. An ambitious program of charmonium and open charm physics, and searches of exotic states, hybrids and glueballs, is planned. There are two clear advantages which this facilty will have over the Cornell program. The energy resolution available at GSI should be an order of magnitude better than that at Cornell, which should be a great advantage in the search of narrow states like $^1P_1$, the D-states, and the radial excitations of the P-states. Unlike the e^+e^- collider at Cornell, at the GSI facility one can also study charmonium and open charm in the nuclear environment by using nuclear targets. If approved, the project is expected to be operational in about 2008.

To summarize, recent developments at Fermilab and BEPC have made significant contributions to the precision spectroscopy of charmonium, but many important questions remain unanswered. Fortunately, the planned new facilities at Cornell and GSI promise to carry the baton forward, and make even more exciting contributions to this very important component of strong interaction physics.

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