PRAMANA
— journal of
physics

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Vol. 62, No. 3
March 2004
pp. 615–622

Charmonium spectroscopy – A review

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Abstract. A review is presented of the latest developments in the spectroscopy of charmonium.

Keywords. Charmonium; quantum chromodynamics.

PACS No. 14.40.Gx

1. Introduction

In 1974 an unexpectedly narrow resonance which decayed strongly into lepton pairs was discovered at Brookhaven (BNL) and Stanford (SLAC). This discovery of J/ψ was quickly recognized as the bound state of a new quark and antiquark, charm and anticharm ($c\bar{c}$), and it inaugurated a new era in hadronic physics. During the next ten years, there was intense activity in the physics of charmonium, but it petered out as particle physics moved on to the heavier, bottom and top quarks. Fortunately, we now have two new and significant developments which are leading to a renewed interest in the precision spectroscopy of $c\bar{c}$ charmonium. These are the successful exploitation of proton–antiproton annihilation in the $\sqrt{s} = 2.9$–4.0 GeV range at Fermilab (FNAL experiments E760, E835), and the BES spectrometer program at BEPC, the electron positron collider at Beijing. Both these experiments are providing high precision data for charmonium states, and are leading to much better understanding of QCD in the non-perturbative regime.

The BES(BEPC) program [1] is modeled after the well-known Mark III (SPEAR) program at SLAC, and it has been churning out results based on a harvest of nine million J/ψ and 3.8 million ψ' in BES I and 58 million J/ψ and 14 million ψ' in BES II.

The Fermilab $p\bar{p}$ program became operative in 1990, and it has had three successful runs, E760 (1990–91) and its successor E835 (1996–97) and E835p (1999–2000) [2].

The Fermilab antiproton source was designed to produce, store, and cool antiprotons at 9 GeV in order to feed the Tevatron collider program. However, when the collider experiments are not running, it is possible to use the stored $\bar{p}$ in the accumulator ring for other experiments. The $\bar{p}$ can be decelerated effectively to

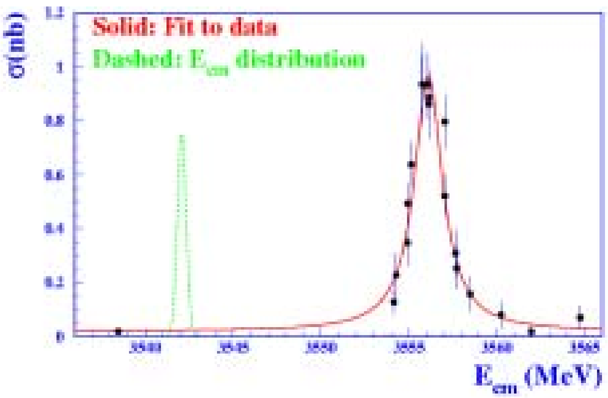

Figure 1. A typical resonance scan (χ_{c2}) in Fermilab E760/E835. The dashed peak represents the instrumental mass resolution function of FWHM $\approx$ 500 keV.

any energy down to $\approx$ 3 GeV. For the charmonium experiments, a cluster jet target of hydrogen intersects the circulating beam in the accumulator ring, and the electromagnetic products of annihilation, photons and electrons, are detected in an azimuthally symmetric detector located around the intersection region. Charmonium resonances are scanned by varying the antiproton energy in small steps, and unprecedented mass resolution ($\approx$ 1 part in 10^4), and energy precision ($\approx$ 1 part in 10^5), are realised. An illustrative scan, one for the χ_{c2} resonance [2], is shown in figure 1. The greatest advantage of $p\bar{p}$ annihilation is that it can form states of all J^{PC}, whereas e^+e^- annihilation can only directly form vector states.

2. Overview of the current status

To put things in perspective, I show the spectra of charmonium in figure 2. Except for J/ψ, most charmonium resonances have had less than 10 hadronic channels measured, and these account for less than $\approx$ 15% of the total hadronic decay branching ratio. More than half the decays measured have errors larger than 30%. The bound states, $\eta_c'(2^1S_0)$ and $h_c(^1P_1)$, as well as the states above the $D\bar{D}$ threshold have not even been identified. This is a regrettable state of affairs [3]. Fortunately, we can expect that a significant improvement in this situation will take place when CLEO-c and the new GSI facility come on-line.

3. The triplet S, or vector states

The $p\bar{p}$ experiments have led to a large revision of the two most important parameters of charmonium physics – the total and e^+e^- widths of J/ψ and ψ'.

The (e^+e^-) results were obtained by indirect measurements of widths (areas under peaks for e^+e^-, $\mu^+\mu^-$ and hadronic decays of J/ψ and ψ'). The Fermilab E760 experiment measured these widths directly by scanning the resonances with

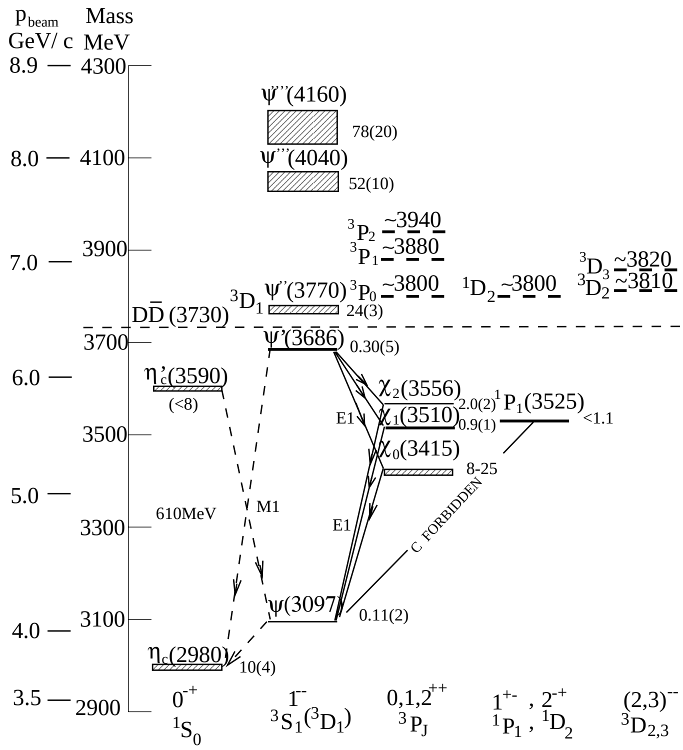

Figure 2. The charmonium spectrum $h_c(^1P_1)$, η_c and states above the $D\bar{D}$ threshold have not been identified.

their high resolution antiproton beam, and showed that the actual widths were as much as 45% larger [2,3].

These new results are expected to have a large impact on many important phenomenological parameters of QCD. For example, the estimate of the vacuum expectation value of the gluon-condensate ($\langle G^2\rangle \equiv \langle 0|(\alpha_s/\pi)G_{\mu\nu}G_{\mu\nu}|0\rangle$) will increase by $\approx 30\%$.

A large number of decays (134) of J/ψ have been measured, albeit only half with errors less than $\pm 30\%$. In contrast, only half that many decays of ψ' have been measured. A comparison of the two leads to the interesting '$\rho - \pi$ problem' to which I refer later.

The unbound vector states, and the r-parameter

All that we know about charmonium above the $D\bar{D}$ breakup threshold at 3729 MeV is from three pre-1980 experiments. These experiments measured the total hadronic cross-sections as functions of $E_{\rm cm}$, and presented their results in terms of the ratio $R = \sigma(\text{hadron})/\sigma(\mu^+\mu^-)$ (see figure 3). As is obvious, there are serious inconsistency problems with data from the different sources [4–6], which can only be resolved by precision measurements of R at CLEO-c. In the meanwhile, the presently listed parameters of $\psi^{\rm III}$, $\psi^{\rm IV}$, $\psi^{\rm V}$ should be considered tentative.

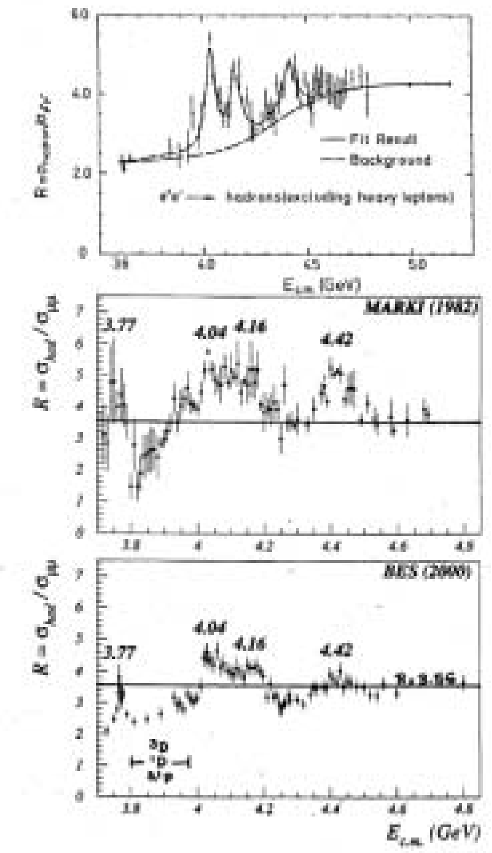

Figure 3. Results from three different measurements of the R-parameter.

It is also worth reminding ourselves that the peculiar decay ratios of $\psi(4040)$ [3] measured in 1978 remain unexplained:

$$\psi(4040) \to D^0\bar{D}^0 : \bar{D}^0 D^* : D^*\bar{D}^* = 1 : 20(11) : 640(380),$$

(as opposed to the naive expectation of 1 : 4 : 7). The experimental results need to be confirmed before any exotic theoretical explanations can be believed.

4. The triplet P or $\chi_J(^3P_J)$ states

Total widths of ^3P_J *states*

The e^+e^- experiments were not very successful in measuring the total widths of χ_J states which they could only populate by the radiative decays of ψ'. The Fermilab $p\bar{p}$ experiments measured these widths directly with good precision [2,7]. This has allowed the detailed study of properties of χ_J states.

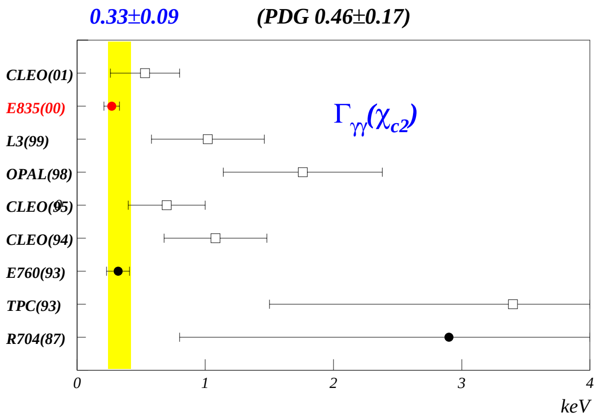

Figure 4. A compilation of results for the two photon width of the χ_2 resonance.

Radiative widths of ^3P_J *states*

The radiative widths, $\chi_J \to \gamma J/\psi$ have been measured directly for χ_1 and χ_2, for which the branching ratios are large (31.6% and 18.7%, respectively). In contrast, because the χ_0 branching ratio is much smaller, being only $\sim 1\%$, and is obtained indirectly, its radiative width cannot be considered well-determined. The precision of the present values for the radiative widths of $\Gamma(\chi_0) = 100(20)$ keV, $\Gamma(\chi_1) = 290(49)$ keV, and $\Gamma(\chi_2) = 390(50)$ keV [3,7], is not good enough to shed light on relativistic and coupled channel effects. Improved results may be expected from CLEO-c.

Two photon widths of ^3P_J *states*

The two methods for measuring $\Gamma_{\gamma\gamma}(\chi_0, \chi_2)$ are via $p\bar{p} \to \chi_{0,2} \to \gamma\gamma$ [8], and $e^+e^- \to e^+e^-(\gamma\gamma) \to e^+e^-(\chi_{0,2}) \to e^+e^-(\chi_{0,2}) \to$ hadrons h_i) [9]. The results from the two methods continue to be different, as is illustrated for χ_2 in figure 4. Since both methods actually measure products of branching ratios, it is conjectured that the discrepancies may have their origin in the knowledge of $\mathrm{Br}(p\bar{p} \to \chi_{0,2})$ and $\mathrm{Br}(\chi_{0,2} \to h_i)$.

5. Spin singlet states

These are generally the most difficult states to access and study. This is because in e^+e^- annihilation it is the spin triplet vector states (J/ψ, ψ', Υ, ...) which are directly formed. Their radiative decay to spin singlet states, $^1S_0(\eta_c, \eta_c')$, is M1 and therefore highly suppressed. In other cases, e.g. $^1P_1(h_c)$, the radiative decay is entirely forbidden by C-conservation. The result is that no singlet state has ever been identified in bottomonium, and only one singlet state, η_c, was, until recently, identified in charmonium.

Singlet S, $\eta_c(1^1S_0), \eta'_c(2^1S_0)$ states

The only singlet resonance which has been unambiguously identified is η_c, the ground state of charmonium, but none of its 20 hadronic decay channels have been measured with better than 30% errors; half of them have only upper limits established. Only one radiative decay, $\eta_c \to \gamma\gamma$, has ever been measured. As in the case of $\chi_{0,2}$; there are large differences between the results obtained by $\gamma\gamma$ fusion experiments, $e^+e^- \to e^+e^- + (\gamma\gamma)_{\eta_c}$, and the $p\bar{p} \to \eta_c \to \gamma\gamma$ experiments. For example, the latest result of the $p\bar{p}$ experiment is $\Gamma_{\gamma\gamma}(\eta_c) = 3.8 \pm 1.1^{+1.9}_{-1.0}$ keV [10] and the latest CLEO result from $\gamma\gamma$ fusion [11] is a factor two larger. Needless to say, better measurements are sorely needed.

The radial excitation of η_c, the $\eta'_c(2^1P_0)$ has been difficult to find. Crystal ball at SLAC claimed to have found it, but no other past experiment succeeded in confirming it. E760 and E835 both have been unsuccessful in finding any evidence for it in the mass range 3575–3660 MeV. At LEP, DELPHI and L3 have been equally unsuccessful in finding η'_c in the two photon fusion reaction $e^+e^- \to e^+e^- + (\gamma\gamma)_{\eta_c}$.

There is a very recent development about η'_c. BELLE has reported evidence for η'_c in the decay $B \to K\eta'_c \to K(K_sK^-\pi^+)$ [12]. They report $M(\eta'_c) = 3654(6)(8)$ MeV. This is rather surprising, because it implies $M(\psi' - M(\eta'_c) = 32(10)$ MeV. Most theoretical predictions for this hyperfine splitting are around 70 MeV, with $M(J/\psi) - M(\eta_c) = 115(2)$ MeV. At CLEO efforts are being made to confirm this identification in their two photon fusion data.

Singlet P, $h_c(^1P_1)$ state, and hyperfine splitting

The splitting between spin singlet and triplet states arises from the spin–spin interaction. For a vector potential this is a contact interaction, proportional to the wave function at the origin. Accordingly, singlet-triplet splitting should exist only in $L = 0$ states. If the confinement part of the $q\bar{q}$ potential is scalar and has no spin–spin component, the p-wave states, $^1P_1$ and the centroid of ^3P_J, should be degenerate. If the p-wave states show $^1P_1 - \langle ^3P_J \rangle$ splitting it has important implications for our understanding of confinement.

Since we know that $M\langle ^3P_J \rangle = (5M(\chi_2) + 3M(\chi_1) + M(\chi_0))/9 = 3525.30(15)$ MeV, the question is to find the $^1P_1$ state of charmonium. The E760 experiment claimed to have identified it with a mass of $M(^1P_1) = 3526.20(25)$ MeV in its isospin forbidden decay to $J/\psi + \pi^0$ [13]. Since then, the successor experiments E835 and E835p have sought to confirm this discovery with much larger luminosity runs. They have not succeeded so far. So, the question of the hyperfine splitting of p-wave states must be considered as still open.

6. The theoretical situation

Lattice calculations are not yet mature enough to provide anything more than mass estimates of charmonium states at the ±15% level. Decay predictions are at present out of question. All we have are predictions based on pQCD and potential models. While these have had reasonable success in predicting masses of low-lying states, they often fail dramatically in other predictions. For example, the hadron-helicity conservation rule of pQCD is strongly violated in the copious production of spin zero states η_c and χ_{c0} in $p\bar{p}$ annihilation. Similarly, the expectation that the ratios $\mathrm{Br}(\psi' \to h_i)/\mathrm{Br}(J/\psi \to h_i)$ should be identical to the ratio $\mathrm{Br}(\psi' \to e^+e^-)/\mathrm{Br}(J/\psi \to e^+e^-) = 0.12$ since both depend on wave functions at the origin, is strongly violated. This leads to the infamous '$\rho - \pi$ problem'. The ratios $\mathrm{Br}(\chi_{c0} \to h_i)/\mathrm{Br}(\chi_{c2} \to h_i)$, predicted to be simply 15/4, exhibits similar problems.

7. The strong coupling constant

The strong coupling constant, α_s, can be determined from charmonium decays by forming ratios of two branching ratios, so that the unknown quark masses and wave functions (or their derivatives) at the origin cancel out. With the new measurements of $\Gamma(gg)$ and $\Gamma(\gamma\gamma)$ for both η_c and χ_2 resonances, rather reliable values of α_s at the charm quark mass have been obtained: $\alpha_s[(\eta_c \to gg)/(\eta_c \to \gamma\gamma)] = 0.33(7)$; $\alpha_s[(\chi_2 \to gg)/(\chi_2 \to \gamma\gamma)] = 0.36(2)$. The average, $\alpha_s(m_c) = 0.35(2)$, extrapolates to $\alpha_s(m_Z) = 0.119(7)(7)$, which is in excellent agreement with the world average $\alpha_s(m_Z) = 0.113(3)$ [3].

8. The future

The Fermilab experiment E835 has ended. Antiprotons at Fermilab are now exclusively devoted to Tevatron physics. The BES program is continuing and will keep on adding to their wealth of J/ψ and ψ', but at this point they are also limited by both luminosity and detector capability.

The future belongs to two new projects. At Cornell, the venerable CESR/CLEO complex is being transformed into CESR-c/CLEO-c with capabilities to do excellent charmonium and open-charm physics in e^+e^- annihilation. It should be operational in less than a year. At GSI, Darmstadt, an ambitious program of charmonium physics is being developed based on a 50 GeV proton synchrotron and a 15 GeV/c antiproton storage ring. This facility should be operational by 2008. So, we can hope that charmonium physics will thrive in the next decade.

Acknowledgement

I wish to acknowledge the help of David Joffe in the preparation of this paper. This work was supported by the U.S. Department of Energy.

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