Charmonium Spectroscopy Below Open Flavor Threshold

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Latest experimental results in the charmonium spectroscopy below $D\bar{D}$ breakup threshold are reviewed.

1. Introduction

Charm quark has large mass (~1.5 GeV) compared to the masses of $u$, $d$, $s$ quarks. Velocity of the charm quarks in hadrons is not too relativistic $(\beta c)^2 \sim 0.2$. Strong coupling constant $\alpha_s(m_c)$ is small (~0.3). Therefore charmonium spectroscopy is a good testing ground for the theories of strong interactions: quantum chromodynamics (QCD) in both perturbative and nonperturbative regimes, QCD inspired purely phenomenological potential models, nonrelativistic QCD (NRQCD) and lattice QCD.

There are 8 bound states of charmonium below the $D\bar{D}$ breakup threshold (Fig. 1). These are spin triplets $J/\psi(1^3S_1)$, $\psi(2S)(2^3S_1)$, $\chi_{c0,1,2}(1^3P_{0,1,2})$ and spin singlets $\eta_c(1^1S_0)$, $\eta_c(2S)(2^1S_0)$, $h_c(1^1P_1)$. Only $J/\psi$ and $\psi(2S)$ can be produced directly in $e^+e^-$ annihilation. A lot is known about these triplet states. Spin singlet states population via radiative transitions from the vector states is either very weak (M1 transition for $\eta_c(1S)$, $\eta_c(2S)$), or C-forbidden ($h_c(1^1P_1)$). Accordingly, little is known about these singlet states.

![Figure 1: Spectra of the states of charmonium below $D\bar{D}$ breakup threshold.](image)

The status of charmonium states below $D\bar{D}$ breakup threshold is summarized in Table I. The masses and widths from PDG 2007, as well as a number of measured decay channels from PDG 2002, 2004 and 2007 are presented separately for spin-triplet and spin-singlet states.

| Spin Triplets | Mass (MeV) | Width (MeV) | Number of Decays |
|---------------|------------|-------------|------------------|
| $J/\psi$      | 3096.92±0.01 | 93.4±2.1 (keV) | 134 135 162 |
| $\psi(2S)$   | 3686.09±0.03  | 327±11 (keV)   | 51 62 115 |
| $\chi_{c0}$  | 3414.75±0.35  | 10.4±0.7       | 17 17 51  |
| $\chi_{c1}$  | 3510.66±0.07  | 0.89±0.05      | 12 13 35  |
| $\chi_{c2}$  | 3556.20±0.09  | 2.05±0.12      | 18 19 37  |

| Spin Singlets | Mass (MeV) | Width (MeV) | Number of Decays |
|----------------|------------|-------------|------------------|
| $\eta_c(1S)$  | 2979.8±1.2  | 26.5±3.5     | 20 21 31  |
| $\eta_c(2S)$  | 3637±4      | 14±7         | 3 4 4  |
| $h_c$          | 3525.93±0.27 | <1           | 3 3 4  |

It is obvious from Table I that the parameters of spin-triplet states are measured with precision, and the number of measured decay channels is large (notice the marked improvements after 2004). This is not valid for spin-singlet states. A lot remains to be done for precision measurements of their parameters and decay channels.

Some new and recent experimental developments on charmonium spectroscopy below open flavor threshold will be reviewed.

2. Observation of $\eta_c(2S)$

It is important to identify the spin-singlet states in order to determine the hyperfine, or spin-spin interaction, which is responsible for singlet-triplet splitting of $q\bar{q}$ states. Identification of $\eta_c(2S)$ is important to know the possible variation of spin-spin interaction from Coulombic ($J/\psi$, $\eta_c(1S)$) to confinement ($\psi(2S)$, $\eta_c(2S)$) regions of the $q\bar{q}$ interaction. Most potential model calculations predicted $M(\eta_c(2S))=3594-3626$ (MeV).

Prior to 2002 there were several unsuccessful attempts to identify $\eta_c(2S)$ in $p\bar{p}$, $\gamma\gamma$-fusion, inclusive photon analysis.

Finally, $\eta_c(2S)$ was first observed in $B$ decays by Belle [4]. It was followed by its observation in $\gamma\gamma$-fusion by CLEO [2] (see Fig. 2 left), and BaBar [3].

Table I Status of charmonium states.
All available measurements of $\eta_c(2S)$ are summarized in Table II. It is obvious that the spread in mass measurements is uncomfortably too large. The PDG 2007 weighted average value of mass is $M(\eta_c(2S)) = 3637 \pm 4$ (MeV). This leads to the hyperfine splitting $\Delta M_{hf}(2S) = 49 \pm 4$ (MeV). The hyperfine splitting value for 1S states is $\Delta M_{hf}(1S) = 117 \pm 1$ (MeV). Explaining large difference between $\Delta M_{hf}(2S)$ and $\Delta M_{hf}(1S)$ is a challenge for theorists. The width of $\eta_c(2S)$ is essentially unmeasured (PDG 2007 value is $\Gamma(\eta_c(2S)) = 14 \pm 7$ (MeV)). Measurement of the width is a challenge to the experimentalists. The decay of $\eta_c(2S)$ is observed only in one decay channel, $\eta_c(2S) \rightarrow K_{s0}K\pi$.

A lot remains to be done about $\eta_c(2S)$. Attempts are being made to identify $\eta_c(2S)$ in the decay $\psi(2S) \rightarrow \eta_c(2S)$ from $54 \, pb^{-1}$ CLEOc $\psi(2S)$ data. Thus, new results are expected from CLEOc.

### Table II Measured parameters of $\eta_c(2S)$ from different experiments (PDG 2007)

| Exper. | $M(\eta_c(2S))$ | $\Gamma(\eta_c(2S))$ | Events(reaction) |
|--------|-----------------|----------------------|------------------|
| Belle[1] | 4654±10 | <55 | 39±11 ($B \rightarrow K_{s0}(K\pi\pi\pi)$) |
| CLEO[2] | 3643.9±3.4 | 63±13.0 | 61±15 ($\gamma \gamma \rightarrow K_{s0}(K\pi\pi)$) |
| BaBar[3] | 3630.8±3.5 | 17.0±8.7 | 112±24 ($\gamma \gamma \rightarrow K_{s0}(K\pi\pi)$) |
| BaBar[4] | 3645.0±8.4 | 22±14 | 121±27 ($e^+e^- \rightarrow J/\psi c\bar{c}$) |
| Belle[5] | 3626±8 | - | 311±42 ($e^+e^- \rightarrow J/\psi c\bar{c}$) |

### 4. Measurements of the $\psi(2S)$ Widths

Using $pp$ annihilation to form charmonium $cc$ states, Fermilab experiment E835 achieved unprecedented precision in measuring masses and widths of charmonium resonances. This happens due to taking advantage of stochastically cooled antiproton beams, with FWHM energy spreads of 0.4-0.5 MeV in the center-of-mass frame.

Recently new precision measurement of the $\psi(2S)$ total width was performed from excitation curves obtained in $pp$ annihilations from 1.64 $pb^{-1}$ scan data in the $\psi(2S)$ region, collected by E835 in 2000 [8]. The channels analyzed were $pp \rightarrow e^+e^-$ and $pp \rightarrow J/\psi X \rightarrow e^+e^- + X$. New technique of “complementary scans”, based on precise beam revolution-frequency and orbit-length measurements was used. Resonance parameters were extracted from a maximum-likelihood fit to the excitation curves. The total width of the $\psi(2S)$ and the combination of partial widths were measured:

- $\Gamma_{tot}(\psi(2S)) = (290 \pm 25 \pm 4) \, keV$
- $\Gamma_{e^+e^-}/\Gamma_{tot} = (579 \pm 38 \pm 36) \, meV$

These represent the most precise measurements to date (Fig. 3).

BES has also measured recently the $\psi(2S)$ total width using $e^+e^-$ annihilation scan data in the $\psi(2S)$ and $\psi(3770)$ regions, collected by BES II in 2003 [8] (Fig. 3). They have analyzed the channel $e^+e^- \rightarrow$
Resonance parameters were extracted from simultaneous fit of cross section curves covering energy ranges of both $\psi(2S)$ and $\psi(3770)$ resonances: $\Gamma_{\text{tot}}(\psi(2S))=(331\pm58\pm2)$ keV, $\Gamma_{ee}(\psi(2S))=(2.330\pm0.036\pm0.110)$ keV.

5. Measurements of the $J/\psi$ Widths

Using 281 pb$^{-1}$ CLEOc $\psi(3770)$ data and looking for radiative return events to $J/\psi$, CLEO has measured the widths of the $J/\psi$ [10]. They selected $\mu^+\mu^-$ events, each with a dimuon mass in the region of the $J/\psi$, and counted the excess over nonresonant QED production. Resulting cross section is proportional to $Br_{\mu\mu} \times \Gamma_{ee}(J/\psi)$. Dividing once more by $Br_{\mu\mu}$ they obtained $\Gamma_{ee}(J/\psi)$.

6. Measurements of the $\eta_c(1S)$ and $\chi_{c0,2}(1P)$ Parameters in Two-Photon Fusion Reaction

The masses and widths of the spin-triplet $\chi_{cJ}(1P)$ states are measured with high precision at Fermilab $p\bar{p}$ experiments E760/E835. But the mass and width of the spin-singlet $\eta_c(1S)$ state are known with only $\sim1$ MeV and $\sim3$ MeV precision respectively.

Using 395 $fb^{-1}$ data sample accumulated with the Belle detector, measurements of the $\eta_c(1S)$ and $\chi_{c0,2}(1P)$, produced in two-photon collisions and decaying to four-meson final states ($4\pi$, $2K2\pi$, $4K$) were performed [12] (Fig. 4).

6.1. Mass and width of the $\eta_c(1S)$ and $\chi_{c0,2}(1P)$

The measured values of the mass and width of $\eta_c(1S)$ and $\chi_{c0,2}(1P)$, and the number of signal events used in analysis are presented in Table III. The values of the mass and width for $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ are consistent within errors with the previous high precision measurements. The precision of the measured mass and width of $\eta_c(1S)$ is comparable to other available precision measurements.

| Resonance     | Mass (MeV)     | Width (MeV)     | N(events)   |
|---------------|----------------|-----------------|-------------|
| $\eta_c(1S)$  | 2986.1±1.0±2.5 | 28.1±3.2±2.2    | 7616±553    |
| $\chi_{c0}(1P)$ | 3414.2±0.5±2.3 | 10.6±1.9±2.6    | 5459±319    |
| $\chi_{c2}(1P)$ | 3555.3±0.6±2.2 |                | 2503±158    |

6.2. Two-photon widths of $\eta_c(1S)$ and $\chi_{c0,2}(1P)$

The two photon decay of the positive C-parity charmonium states in the lowest order is a pure QED process. The measurements of the two photon partial widths of these states can shed light on higher order relativistic and QCD radiative corrections.
The values of the two photon partial widths of \( \eta_c(1S) \) and \( \chi_{c0}(1P) \), evaluated from the measurements of the \( \Gamma_{\gamma\gamma} \times Br \) by Belle \cite{12}, are presented in Table IV. They are compared to the values obtained from the PDG 2007. The Belle value of \( \Gamma_{\gamma\gamma}(\eta_c) \) is \( \sim 2.7 \) times smaller (\( \sim 4\sigma \) difference) than the PDG 2007 value. The values of \( \Gamma_{\gamma\gamma}(\chi_{c0}) \) and \( \Gamma_{\gamma\gamma}(\chi_{c2}) \) are consistent within errors with those from the PDG 2007.

The ratio \( R \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0}) \) is an interesting quantity, because it allows us to evaluate the reliability of the first order radiative corrections, which are often very large, by calculating \( \alpha_s \) from them

\[
R \equiv \frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c0})} = \frac{(4\Psi(0))^3\alpha_s^2/\alpha_s^2}{(15\Psi(0))^2\alpha_s^2/\alpha_s^2} \times (1-1.7\alpha_s) = 0.267(1-1.76\alpha_s)
\]

The Belle value \( R=0.221\pm0.041 \) leads to \( \alpha_s=0.098\pm0.085 \), which is obviously underestimate of \( \alpha_s(m_c) \), which is known to be \( \sim 0.3 \). This makes questionable the reliability of nearly 50% first order correction factor for \( \Gamma_{\gamma\gamma}(\chi_{c2}) \).

Table IV Two photon partial widths \( \Gamma_{\gamma\gamma} \) of \( \eta_c(1S) \), \( \chi_{c0}(1P) \) and \( \chi_{c2}(1P) \) \cite{12}. \( \Gamma_{\gamma\gamma} \) values are evaluated from measured \( \Gamma_{\gamma\gamma} \times Br \) using branching fractions from PDG 2007. Results of 4\( \pi \), 2\( K \)2\( \pi \) and 4\( K \) channels are combined.

| Resonance | \( \Gamma_{\gamma\gamma} \) (keV), Belle | \( \Gamma_{\gamma\gamma} \) (keV), PDG 07 |
|-----------|--------------------------------------|--------------------------------------|
| \( \eta_c(1S) \) | 2.46\( \pm \)0.60 | 6.7\( \pm \)0.9 |
| \( \chi_{c0}(1P) \) | 1.98\( \pm \)0.24 | 2.90\( \pm \)0.43 |
| \( \chi_{c2}(1P) \) | 0.438\( \pm \)0.062 | 0.539\( \pm \)0.050 |
| \( R \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0}) \) | 0.221\( \pm \)0.041 | 0.186\( \pm \)0.032 |

7. Summary

All Charmonium states below open flavor threshold have now been firmly identified.

The spectroscopy of spin-triplet states is now well in hand, but a lot still needs to be done for spin-singlet states. Masses, widths, particularly of \( \eta_c(2S) \) and \( h_c(1^1P_1) \) need to be better determined. Many more decay channels need to be investigated for each.

A large number of investigations, based on the world’s largest sample of \( \psi(2S) \) acquired by CLEOc, are currently in progress, and results are expected soon. These include:

- Precision results for mass, width and branching fractions of \( h_c(1^1P_1) \);
- Results for many decay channels of \( \eta_c(1S) \);
- Results for attempt to identify \( \eta_c(2S) \) in radiative decay of \( \psi(2S) \);
- Results of studies for \( pp \) threshold enhancement in radiative decays of \( J/\psi, \psi(2S) \);
- Results of search for tensor glueball, \( \xi(2230) \);
- Hadronic and radiative decays of \( \psi(2S) \) and \( J/\psi \);
- Two-body and multi-body decays of \( \chi_{cJ}(1P) \) states, and others.

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