Charmonium spectroscopy and decays

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In this talk, I review the recent experimental developments on charmonium. These mainly include the precision measurements of spin-singlet states \( \eta_c \), \( \eta_c'(2S) \), \( h_c \), studies of the charmonium-like states \( X(3872) \) and the \( Y \) states. Charmonium transitions and decays are also discussed.

**Introduction**

Charmonia are charmed-quark and anticharmed-quark states \((c\bar{c})\) bound by the strong interaction. Charmed quarks are heavy, so the motion of the charm quark inside the bound state is slow, \( \nu^2 \sim 0.3 \), where \( \nu \) is relative velocity between the \( c \) and \( \bar{c} \). The charmonium system can be approximately considered as a non-relativistic bound state. The energy levels can be found by solving a non-relativistic Schrodinger equation, with sophisticated corrections (e.g. relativistic correction) and other effects. Figure 1 shows the charmonium levels from this approach [1]. Although all charmonium states below the \( \bar{D}D \) mass threshold have been observed, knowledge is sparse on spin-singlet S-wave \( \eta_c(1S_0) \), the \( \eta_c(2S)(2^1S_0) \), and the P-wave \( h_c(1P_1) \). Above the threshold, the spin-triplet S-wave states \( \psi(4040) \), and \( \psi(4415) \), and the D-wave \( \psi(3770) \), and \( \psi(4160) \) have been found. The \( \psi(4040) \), \( \psi(4415) \), \( \psi(3770) \), \( \psi(4160) \) are commonly assigned as \( \psi(3^3S_1) \), \( \psi(4^3S_1) \), \( \psi(1^3D_1) \) and \( \psi(2^3D_1) \), respectively. The \( Z(3930) \) observed by Belle [2] in the \( \bar{D}D \) mass distribution from \( e^+e^- \rightarrow e^+e^-\bar{D}ar{D} \) events, is identified with \( \chi_{c2}^+ \) \((2^3P_2)\).

The \( h_c \) \((1^1P_1)\)

Information about the spin-dependent interaction of heavy quarks can be obtained from precise measurement of the \( 1^P \) hyperfine mass splitting \( \Delta M_{hf} \equiv \langle M(1^3P) \rangle - M(1^1P) \), where \( \langle M(1^3P) \rangle = \langle M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2}) \rangle / 9 = 3525.30 \pm 0.04 \text{ MeV/c}^2 \) [3] is the spin-weighted centroid of the \( 3^3P_1 \) mass and \( M(1^1P) \) is the mass of the singlet state \( h_c \). A nonzero hyperfine splitting may give an indication of non-vanishing spin-spin interactions in charmonium potential models [1].

With 106M \( \psi' \) events, BESIII observed clear signals in the \( \pi^0 \) recoil mass distribution for \( \psi' \rightarrow \pi^0 h_c \) with and without the subsequent radiative decay \( h_c \rightarrow \gamma \eta_c \) [3], as shown in Fig. 2. They reported first measurements of the absolute branching ratios \( B(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4} \) and \( B(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\% \), along with improved measurements of the \( h_c \) mass \( M(h_c) = 3525.40 \pm 0.13 \pm 0.18 \text{ MeV/c}^2 \). They found the \( 1^P \) hyperfine mass splitting to be \( \Delta M_{hf} \equiv \langle M(1^3P) \rangle - M(1^1P) = -0.10 \pm 0.13 \pm 0.18 \text{ MeV/c}^2 \), which is consistent with no strong spin-spin interaction. The results are in agreement with CLEO-c’s earlier results [4].

In addition, BESIII used 16 exclusive hadronic \( \eta_c \) decay modes to reconstruct \( h_c \rightarrow \gamma \eta_c \). By doing so, the ratio of signal to background can be improved significantly. A simultaneous fit to the \( \pi^0 \) recoil mass distributions of the 16 decay modes was performed. From 106M \( \psi' \) events, 835 \pm 35 signal events are found. The measured \( h_c \) mass and width are \( m = 3525.31 \pm 0.11 \pm 0.15 \text{ MeV/c}^2 \), and \( \Gamma = 0.70 \pm 0.28 \pm 0.25 \text{ MeV} \), which are consistent with the inclusive analysis results, and also consistent with CLEO-c’s results [4].

The \( \eta_c(2S) \)

The radially excited \( n = 2 \) spin-singlet S-wave state, the \( \eta_c(2S) \) meson, was not well established until the Belle collaboration found the \( \eta_c(2S) \) signal at...
3654 ± 6(stat) ± 8(syst) MeV/c² in the $K_S^0 K^+\pi^-$ invariant mass distribution in a sample of exclusive $\eta_c(2S) \rightarrow K_SK^-\pi^-$ decays [11]. Since then measurements of $\eta_c(2S)$ in photon-photon fusion to $KK\pi$ final state have been reported [8][10], as well as in double charmonium production [11][12]. CLEO-c searched for $\eta_c(2S)$ in the radiative decay $\psi' \rightarrow \gamma \eta_c(2S)$, found no clear signals in its sample of 25M $\psi'$ [13]. The challenge of this measurement is the detection of 50 MeV photons.

With 519 fb$^{-1}$, BaBar observed $\eta_c(2S) \rightarrow K_SK^+\pi^-$ and $\eta_c(2S) \rightarrow K^+K^-\pi^+\pi^-\pi^0$ produced in photon-photon fusion for the first time [14]. They measured the mass and width of $\eta_c$ and $\eta_c(2S)$ in $K_SK^+\pi^-$ decays, $m(\eta_c(1S)) = 2982.5 \pm 0.4 \pm 1.4$ MeV/c², $\Gamma(\eta_c(1S)) = 32.1 \pm 1.1 \pm 1.3$ MeV, $m(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8$ MeV/c², $\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2$ MeV. These $\eta_c(2S)$ results are so far the most precise measurements.

Belle updated the analysis of $B^\pm \rightarrow K^\pm \eta_c$ and $B^\pm \rightarrow K^\pm \eta_c(2S)$ followed by $\eta_c$ and $\eta_c(2S)$ decay to $K_SK^+\pi^-$ with 535 million $BB$-meson pairs [15]. Both decay channels contain the backgrounds from $B^\pm \rightarrow K^\pm K_SK^+\pi^-$ decays without intermediate charmonia, which could interfere with the signal. Belle’s analysis took interference into account with no assumptions on the phase or absolute value of the interference. A two dimensional $M(K_SK^+\pi^-) - \cos \theta$ fit was performed to extract signal, where $\theta$ is the angle between $K$ (from $B$ directly) with respect to $K_S$ in the rest frame of the $K_S^0 K^+\pi^-$. They obtained the masses and widths of $\eta_c$ and $\eta_c(2S)$. For the $\eta_c$ meson parameters the model error is negligibly small: $M(\eta_c) = 2985.4 \pm 1.5(stat)_{-0.9}^{+0.2}(syst)$ MeV/c², $\Gamma(\eta_c) = 35.1 \pm 3.1(stat)_{-1.5}^{+1.0}(syst)$ MeV/c². For the $\eta_c(2S)$ meson the model and statistical uncertainties cannot be separated: $M(\eta_c(2S)) = 3636.1_{-3.9}^{+3.7}(stat + model), \Gamma(\eta_c(2S)) = 6.8_{-5.1}^{+8.4}(stat + model)_{-2.9}^{+2.6}(syst)$ MeV/c².

Using 106 million $\psi'$ events, BESIII searched for $\eta_c(2S)$ in the decay $\psi' \rightarrow \eta_c(2S)$ with $\eta_c(2S) \rightarrow K_SK^+\pi^-$. Figure 3 shows the invariant mass distribution of $K_SK^+\pi^-$, where a three-constraints kinematic fit has been applied (in which the energy of the photon is allowed to float). The solid curve in Fig. 3 shows preliminary results of an unbinned maximum likelihood fit with four components: signal, $\chi_{c1}$, $\chi_{c2}$ and other background (coming from $\psi'$ decays to $\pi^0 K_SK^+\pi^-$, $K_SK^+\pi^-\pi^0$ and ISR/FSR production of $K_SK^+\pi^-\gamma_{ISR}/\gamma_{FSR}$). The fit, in which the width of the $\eta_c(2S)$ is fixed at 12 MeV, yields 50.6 ± 9.7 signal events, and gives the mass $M(\eta_c(2S)) = 3638.5_{-2.3}^{+2.3} \pm 1.0$ MeV/c². The statistical significance of the signal is more than 6$\sigma$. Using the detection efficiency determined from MC simulation, the product branching fraction is obtained $B(\psi' \rightarrow \gamma \eta_c(2S)) \times B(\eta_c(2S) \rightarrow K_SK^+\pi^-) = (2.98 \pm 0.57 \pm 0.48) \times 10^{-6}$. Using the result $B(\eta_c(2S) \rightarrow K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)$% from BaBar [16] gives the branching fraction $B(\psi' \rightarrow \gamma \eta_c(2S)) = (4.7 \pm 0.9 \pm 3.0) \times 10^{-4}$. This result is consistent with CLEO-c’s upper limit [13] and predictions of potential models [17].
The \( \eta_c(1S) \)

The mass and width of the lowest lying charmonium state, the \( \eta_c(1^1S_0) \), continue to have large uncertainties when compared to those of other charmonium states [3]. Early measurements of the properties of the \( \eta_c \) using \( J/\psi \) radiative transitions [18, 19] found a mass and width of 2978 MeV/c\(^2\) and 10 MeV, respectively. However, recent experiments, including photon-photon fusion and \( B \) decays, have reported a significantly higher mass and a much wider width \([8, 9, 20, 21]\). The most recent study by the CLEO-c experiment, using both \( \psi' \rightarrow \gamma \eta_c \) and \( J/\psi \rightarrow \gamma \eta_c \), pointed out a distortion of the \( \eta_c \) line shape in \( \psi' \) decays \([22]\). CLEO-c attributed the \( \eta_c \) line-shape distortion to the energy dependence of the “hindered” \( M1 \) transition matrix element.

At BESIII, the \( \eta_c \) can be produced through \( \psi' \rightarrow \gamma \eta_c \), and the \( \eta_c \) mass and width are determined by fits to the invariant mass spectra of exclusive \( \eta_c \) decay modes. Six modes are used to reconstruct the \( \eta_c \): \( K_S K^+\pi^- \), \( K^+ K^-\pi^0 \), \( \eta \pi^+ \pi^- \), \( K_S K^+\pi^- \pi^- \), \( K^+ K^-\pi^+ \pi^- \), and \( 3(\pi^+ \pi^-) \), where the \( K_S \) is reconstructed in \( \pi^+ \pi^- \), and the \( \eta \) and \( \pi^0 \) in \( \gamma \gamma \) decays. Figure 4 shows the \( \eta_c \) invariant mass distributions for selected \( \eta_c \) candidates, together with the estimated \( \pi^0 X_i \) backgrounds (\( X_i \) represents the \( \eta_c \) final states under study), the continuum backgrounds normalized by luminosity, and other \( \psi' \) decay backgrounds estimated from the inclusive MC sample. A clear \( \eta_c \) signal is evident in every decay mode. The \( \eta_c \) signal has an obviously asymmetric shape that suggests possible interference with a non-resonant \( \gamma X_i \) amplitude. The fitted relative phases between the signal and the non-resonant component from each mode are consistent within 3\( \sigma \), which may suggest a common phase in all the modes under study. A fit with a common phase (i.e. the phases are constrained to be the same) describes the data well. The preliminary results on the \( \eta_c \) mass and width are \( M = 2984.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.}) \) MeV/c\(^2\), \( \Gamma = 30.5 \pm 1.0(\text{stat.}) \pm 0.9(\text{syst.}) \) MeV.

Figure 5 compares the recent measurements of the \( \eta_c \) and \( \eta_c(2S) \) mass and width from two photon-photon fusion, \( \psi' \) transition, and \( B \) decays. These results are in good agreement. Hyperfine splittings are \( \Delta M(1S) = 112.5 \pm 0.8 \) MeV, and \( \Delta M(2S) = 47.6 \pm 1.7 \) MeV, which agree well with recent lattice computations [23].

**Charmonium-like states**

The \( X(3872) \) was first observed as a narrow peak in the \( \pi^+ \pi^- J/\psi \) invariant mass spectrum near \( D^*0 D^0 \) threshold from \( B \rightarrow K \pi^+ \pi^- J/\psi \) decays by Belle [24] in 2003, and later confirmed by BaBar [25]. The \( X(3872) \rightarrow \pi^+ \pi^- J/\psi \) decay was also observed inclusively in prompt production from \( p\bar{p} \) collisions at the Tevatron by both CDF [26] and D0 [27]. CDF studied the angular distributions and correlations of the \( \pi^+ \pi^- J/\psi \) final state, found that the dipion was favored to originate from \( J/\psi \rightarrow \pi^+ \pi^- \), and thus only \( J^{PC} = 1^{++} \) and \( 2^{-+} \) explained their measurements [28]. A number of theoretical models have been proposed...
for the $X(3872)$ states, such as conventional charmonium state, $DD^*$ molecules, diquark-diantiquarks, $cc$-gluon hybrids etc., but none can comfortably account for all experimental results. Charmonium states $1^{+} \chi_{c1}(2P)$ and $2^{-} \eta_{c2}(1D_2)$ are possible candidate states for the $X(3872)$. For a $\chi_{c1}(2P)$ state, a large $\chi_{c1}(2P) \to \gamma J/\psi$ branching fraction is expected; experimental results do not agree. For a $\eta_{c2}(1D_2)$ state, a large width is expected; but the observed $X(3872)$ is narrow. In the $DD^*$ molecule model it is hard to explain the large radiative decay rate, the $\pi\pi J/\psi$ rate and the production in $p\bar{p}$. The diquark-diantiquarks model predicts partners for the $X(3872)$, but no partner has been found yet. For $cc$-gluon hybrids, the mass is too low.

The mass of $X(3872)$

With 2.4 fb$^{-1}$ data, CDF presented an analysis of the mass of the $X(3872)$ reconstructed via its decay to $\pi \pi J/\psi$ [29]. They found $\sim 6$ K candidates, shown in Fig. 6. They measured the $X(3872)$ mass $M_X = 3871.61 \pm 0.16$ (stat) $\pm 0.19$ (syst) MeV/c$^2$, which is the most precise determination to date. In EPS2011, LHCb presented measurements of the $X(3872)$ mass of $M_X = 3871.97 \pm 0.46 \pm 0.1$ with 35 pb$^{-1}$ data. Belle also updated the mass and width measurements with 711 fb$^{-1}$ data [30]. A new world average that includes these new measurements and other results that use the $\pi\pi J/\psi$ decay mode is $M_X = 3871.67 \pm 0.17$ MeV/c$^2$.

An important feature of the $X(3872)$ is its mass close to the $D^0 D^{*0}$ threshold. A possible interpretation is that the $X(3872)$ is a molecule-like arrangement comprised of a $D^{*0}$ and a $\bar{D}^0$ [31, 32]. Crucial to these models is whether the $X(3872)$ mass is below or above $m(D^{*0}) + m(D^0)$. Taking the $D^0$ and $D^{*0}$ mass from PDG 2010, $m(D^{*0}) + m(D^0) = 3871.79 \pm 0.30$ MeV/c$^2$. The new world average is $0.12 \pm 0.35$ MeV/c$^2$ lower than $m(D^{*0}) + m(D^0)$, as shown in Fig. 7.

Search for $X(3872)$ partners

Models of tightly bound diquark-antidiquark system feature two neutral and one charged partner states [33]. The $X(3872)$, observed in $B^+ \to \gamma J/\psi$, is interpreted as a $c\bar{u}c\bar{d}$ combination. In $B^0 \to \bar{K}S \pi^+ \pi^- J/\psi$, one should see a partner state, the $c\bar{d}c\bar{s}$ combination. The two states differ in mass by a few MeV. In addition, a neutral $c\bar{d}c\bar{s}$ partner and a charged (cuc\bar{d}) partner are also expected by isospin and flavor-SU(3).

BaBar [25] and Belle [30] measured the $X(3872)$ mass for $B^+ \to K^+ \pi^+ \pi^- J/\psi$ and $B^0 \to K_S \pi^+ \pi^- J/\psi$ decays, separately. They found mass differences that are consistent with zero, $\Delta M_x = -0.69 \pm 0.97 \pm 0.19$ MeV/c$^2$ for Belle, and $\Delta M_x = 2.7 \pm 1.6 \pm 0.4$ MeV/c$^2$ for BaBar. The possibility that the $X(3872)$ enhancement in $\pi^+ \pi^- J/\psi$ is composed of two different narrow states, $X_L$ and $X_H$, was addressed by CDF [29]. By fitting their $\sim 6000$ event $X(3872) \to \pi^+ \pi^- J/\psi$ peak with two different Gaussian functions, they found $X_L$ and $X_H$ have masses closer than 3.6 MeV for equal $X_L$ and $X_H$ production.

BaBar searched for a charged partner of the $X(3872)$ in the $\pi^+ \pi^- J/\psi$ mass distribution from $B \to K \pi^+ \pi^- J/\psi$ decays, and found no evidence for a signal in either $B^0$ or $B^+$ decays [34]. They determined the

![FIG. 6: Invariant mass distribution of the X(3872) candidates. The points show the data distribution, the full line is the projection of the unbinned maximum-likelihood fit, and the dashed line corresponds to the background part of the fit. The inset shows an enlargement of the region around the X(3872) peak. Residuals of the data with respect to the fit are displayed below the mass plot.](image)

![FIG. 7: Comparison of the mass measurements of the X(3872).](image)
upper limits $\mathcal{B}(B^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 5.4 \times 10^{-6}$, $\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 22 \times 10^{-6}$ at 90% CL. The Belle limits for the same quantities at 90% CL are $\mathcal{B}(B^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.2 \times 10^{-6}$, $\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 6.1 \times 10^{-6}$ \cite{30}. The results rule out the isospin triplet model for the $X(3872)$.

The $X(3872) \to \gamma J/\psi(\psi')$

Using a data sample of 465 million $BB$ pairs, BaBar searched for $B \to c\bar{c}\gamma K$ decays, found evidence for $X(3872) \to J/\psi \gamma$ and $X(3872) \to \gamma \gamma$ with 3.6 $\sigma$ and 3.5 $\sigma$, respectively \cite{35}. They measured the product of branching fractions $\mathcal{B}(B^0 \to X(3872)K^\pm)$ \cdot $\mathcal{B}(X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-5}$ and $\mathcal{B}(B^+ \to X(3872)K^\pm) \cdot \mathcal{B}(X(3872) \to \psi'\gamma) = (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$, and obtained the ratio $\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4$. The relatively large branching fraction of $X(3872) \to \psi'\gamma$ is generally inconsistent with a purely $D^0 D^{*0}$ molecular interpretation of the $X(3872)$, and possibly indicates mixing with a significant $c\bar{c}$ component.

With 772 million $BB$ events, Belle observed $X(3872) \to J/\psi\gamma$ in the charged decay $B^+ \to X(3872)K^+$ with a significance of 4.9$\sigma$, while in a search for $X(3872) \to \gamma \psi'$ no significant signal was found \cite{36}. They measured the branching fractions $\mathcal{B}(B^+ \to X(3872)K^\pm) \cdot \mathcal{B}(X(3872) \to J/\psi\gamma) = (1.78_{-0.44}^{+0.48} \pm 0.12) \times 10^{-6}$, and provided upper limit on the branching fraction $\mathcal{B}(B^+ \to X(3872)K^\pm)$ \cdot $\mathcal{B}(X(3872) \to \psi'\gamma) < 3.45 \times 10^{-6}$. The upper limit on the ratio $\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} < 2.1$ (at 90% CL).

This results of $X(3872) \to \gamma J/\psi$ from Belle and BaBar are consistent, while the $X(3872) \to \gamma \psi'$ results are in disagreement. More data is need to confirm these results.

The $B \to K\pi X(3872)$

The production characteristic of the $X(3872)$ in $p\bar{p}$ collisions, such as the $p_T$ and rapidity distributions and the ratio of prompt production versus production via $B$-meson decays, are very similar to those of the well established $\psi'$ charmonium state \cite{27}. Thus it is of interest to compare production characteristics of the $X(3872)$ to those of other charmonium states in $B$ meson decays. One common characteristic of all of the known charmonium states that are produced in $B$ meson decays is that when they are produced in association with a $K\pi$ pair, the $K\pi$ system is always dominated by a strong $K^*(890) \to K\pi$ signal.

Belle studied the $X(3872)$ production in association with a $K\pi$ in $B^0 \to K^+\pi^- \pi^+\pi^- J/\psi$ decays \cite{37}. In a sample of 657M $BB$ pairs, about 90 $\pi^+\pi^- J/\psi$ signal events are seen. Figure 8 shows the $K\pi$ invariant mass distribution for these events, where it is evident that most of the $K\pi$ pairs have a phase space like distribution, with little or no signal for $K^*(890) \to K\pi$. All of the events in the $K^*$ peak seem to be due to the side-band determined background. This is contrasted to the $B \to K\psi'$ events (with $\psi' \to \pi^+\pi^- J/\psi$) in the data sample, where the $K\pi$ invariant mass distribution, shown in Fig. 9, is dominated by the $K^*(890)$.

The $X(3872)$ state remains a mystery. Better understanding demands more experimental constraints and theoretical insight.

The $Y$ states

$Y(4260)$, the first unexpected vector charmonium-like state, was observed by BaBar \cite{38} in ISR production of $Y(4260) \to \pi\pi J/\psi$. CLEO \cite{39} and Belle \cite{40} confirmed the BaBar result, but Belle also found an additional broader structure at 4008 MeV/$c^2$. BaBar found \cite{41} another enhancement, $Y(4360)$ in $\pi^+\pi^- \psi'$,
which Belle measured with larger mass and smaller width, Belle also found \[42\] a second structure near 4660 MeV/c².

There is only one unassigned \(1^-\) charmonium state in this mass region, the \(3^3D_1\), and no room to accommodate all of the four observed peaks. Figure 10 shows the \(\bar{D}D\) cross sections. No enhancement is seen for any \(Y \rightarrow D^{(*)}D^{(*)}\). The absence of any evidence for \(Y(4260)\) (\(Y(4360)\)) decays to open charm implies that the \(\pi^+\pi^- J/\psi(\pi^+\pi^-\psi')\) partial width is large. Ref. \[44\] gives \(\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi) > 508\) keV at 90% CL, an order of magnitude higher than expected for conventional vector charmonium. Charmonium would also feature dominant open charm decays, exceeding those of dipion transitions by a factor expected to be \(> 100\), as is the case for the \(\psi(3770)\) and \(\psi(4160)\).

At the EPS2011 conference, Belle presented an analysis of \(Y(4260) \rightarrow \pi^0\pi^0 J/\psi\). They measured \(\Gamma_{\psi^0} \mathcal{B}(J/\psi) = 3.19^{+1.82}_{-1.53} + 0.64 - 0.35\) eV, which is about half of the \(\Gamma_{\psi^0} \mathcal{B}(\pi^+\pi^- J/\psi) = 5.9^{+1.2}_{-0.9}\) eV \[33\]. This is consistent with the CLEO’s study \[39\] on direct production of \(Y(4260)\) in \(e^+e^-\) collisions. It implies that the \(Y(4260)\) has \(I = 0\), as expected for a \(c\bar{c}\) state.

The decay \(\psi' \rightarrow \gamma\pi^0, \gamma\eta\)

The study of vector charmonium decay to a photon and neutral pseudoscalar meson \(P = (\pi^0, \eta, \eta')\) provides experimental constraints on the relevant QCD predictions, such as the vector meson dominance model (VDM), two-gluon couplings to \(q\bar{q}\) states, mixing of \(\eta_c - \eta'\). The ratio \(R_n = \mathcal{B}(\psi(nS) \rightarrow \gamma\eta)/\mathcal{B}(\psi(nS) \rightarrow \gamma\eta')\) is predicted by first order perturbation theory, and \(R_1 \approx R_2\) is also expected \[46\]. However, CLEO-c reported measurements for the decays of \(J/\psi, \psi'\) and \(\psi''\) to \(\gamma P\), and no evidence for \(\psi' \rightarrow \gamma\eta\) or \(\gamma\pi^0\) was found \[47\]. Therefore, they obtained \(R_2 << R_1\) with \(R_2 < 1.8\%\) at 90% CL. Such a small \(R_2\) is unanticipated, and it poses a significant challenge to our understanding of the \(c\bar{c}\) bound states. Do other processes contribute? Is this related to the \(\rho\pi\) puzzle \[48\]?

With 106M \(\psi'\) events, BESIII observed \(\psi' \rightarrow \gamma\pi^0\) and \(\psi' \rightarrow \gamma\eta\) and \(\psi' \rightarrow \gamma\eta'\), where \(\eta\) is reconstructed from \(\eta \rightarrow \pi^+\pi^-\pi^0\) and \(\pi^0\pi^0\pi^0\), and \(\eta'\) is reconstructed from \(\eta' \rightarrow \pi^+\pi^-\eta\) and \(\eta' \rightarrow \gamma\pi^+\pi^-\) \[19\], as shown in Fig. 11. The measured branching fractions are summarized in Table. 1. The \(R_2\) is about 20 times smaller than \(R_1\). \(Q = \mathcal{B}(\psi' \rightarrow \gamma P)\) for each decay mode is also shown in the table, which is much smaller than 12%.
The decay $\chi_{cJ} \to \gamma V, VV$

$\chi_{cJ}$ events make significant contributions to the radiative decays of $\psi'$. The decay of the P wave $\chi_{cJ}$ to $\gamma V$ provides a good chance to validate theoretical predictions and search for glueballs. CLEO-c found a surprisingly large $\chi_{cJ} \to \gamma V$ branching fraction, an order of magnitude higher than the pQCD prediction. With 106M $\psi'$ events, BESIII studied the decays $\chi_{cJ} \to \gamma V$, with $V$ representing $\rho^0$, $\omega$, and $\phi$. The results are listed in Table II where the decay $\chi_{c1} \to \gamma \phi$ is the first observation. The results provide tight constraints on QCD.

Vector pair decay modes are measured at BESIII. In the analysis, $\chi_{cJ}$ candidates are reconstructed with $\phi \phi$, $\omega \omega$, and $\omega \phi$, respectively. The helicity selection rule suppressed decays $\chi_{c1} \to \phi \phi$/$\omega \omega$ are observed for the first time and there is an evidence of the doubly OZI suppressed decay $\chi_{c1} \to \omega \phi$ with a significance of 4.1.$\sigma$.

BESIII searched for $\eta_c(2S) \to VV$ decays using 106M $\psi'$ events, where $VV$ represents $\rho^0 \rho^0$, $K^{*0} K^{*0}$ and $\phi \phi$. They found no evidence for $\eta_c(2S) \to VV$ signal, and determined 90% limits on the branching fractions, which are lower than the theoretical predictions.

**Summary**

Charmonium is the best understood hadronic system. All the lowest-lying charmonium states have been found; the long-anticipated states have been measured with high precision, good agreement between their measured properties and theory. High-mass charmonium meson searches have produced surprises; unanticipated states showed up.

Enormous progress has been achieved on charmonium decays. Many expected decays and transitions have either been measured with high precision or for the first time.

Belle, BaBar, CLEO, CDF and D0 have produced fruitful results in the past. LHC is starting to produce physics results. Large data samples from LHC will allow identification of the X, Y, Z states, and measurements of production, and polarization. BESIII will continue to study charmonium physics. Future experiments, such as PANDA, will complement the activities at other labs.

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