Ground-state studies of charmonium via radiative transitions at BESIII

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Ground-state studies of charmonium via radiative transitions at BESIII

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Abstract. Charmonium states consist of a heavy charm-anticharm quark pair (c\bar{c}), bound by the strong interaction. Theoretically, charmonium can be analyzed based on a non-relativistic framework, since the motion of the charm quark inside the bound state is \(v^2 \sim 0.3\), where \(v\) is relative velocity between the \(c\) and \(\bar{c}\) with the additional of relativistic corrections. All the narrow charmonium states below the open-charm threshold have been experimentally identified and their mass spectrum can be reasonably well described by potential models that incorporate a color Coulomb term at short distances and a linear scalar confining term at large distances. Although all charmonium states below the \(D\bar{D}\) mass threshold have been observed, knowledge is sparse on spin-singlet S-waves, \(\eta_c(1S)\) and \(\eta_c(2S)\). The BESIII/BEPCII facility in Beijing, China, has shed light on these spin-singlet states by collecting a new record of \(\psi(3686)\) decays in electron-positron annihilations.

1. Introduction
The \(\eta_c\) state of charmonium, occupies a special place in the study of heavy quarkonia. It is the only ground state of a heavy quarkonium system which has been experimentally identified and it is the only confirmed heavy quarkonium singlet state. \(\eta_c\) cannot be formed directly in \(e^+e^-\) annihilation, but it can be indirectly production via radiative magnetic-dipole (M1) transitions. Radiative transitions in particular have recently been the subject of both lattice QCD calculations [1] and effective field theory techniques [2]. Among these are the most poorly understood M1 transitions \(J/\psi \rightarrow \gamma \eta_c\) and \(\psi(3686) \rightarrow \gamma \eta_c\). These two transitions are different ways to populate the ground state of charmonium below the open-charm threshold. The experimental challenge lies in the relatively small branching fraction involved in these M1 transitions since the process involves a charm-quark spin flip. Not only are precision measurements needed to validate our theoretical understanding, precise measurements of these M1 transitions are critical for normalizing \(\eta_c\) branching fractions, a key input to extracting other properties such as partial width of the \(\eta_c\) to two photons. The \(J/\psi\) and \(\psi(3686)\) transitions are also a source of information on the \(\eta_c\) mass and width. There is currently a 3.3\(\sigma\) inconsistency between previously measured \(J/\psi\) and \(\psi(3686)\) \(\rightarrow \gamma \eta_c\) and \(\gamma\gamma\) or \(p\bar{p}\) production [3].

2. Spin singlet states: \(\eta_c(1S), \eta_c(2S)\)
The spin-spin interaction term in potential model causes the splitting between \(\eta_c\) and \(J/\psi\) and the \(\eta_c(2S)\) and \(\psi(3686)\) as well, which are called the 1S and 2S hyperfine splitting, respectively. The mass of \(\eta_c(1S)\) and \(\eta_c(2S)\) is of particular interest since the hyperfine splittings provide
Figure 1. Mass splittings of states lying below the open-charm threshold in units of MeV. Left panel shows the mass splitting between 1S states and right panel between 2S states. In each plot, cross and circle symbols indicate the experimental data and theoretical results obtained from the non-relativistic potential model with the lattice inputs, respectively. The results of the lattice spectroscopy is shown with a square symbol [4].

valuable information about the underlying $c\bar{c}$ confinement potential. Figure 1 shows one of the most recent comparison between lattice QCD and experimental results of hyperfine mass splitting $M_{J/\psi} - M_{\eta_c}(1S)$ and $M_{\psi(3686)} - M_{\eta_c}(2S)$. In each plot, cross and circle symbols indicate the experimental data and theoretical results obtained from a non-relativistic potential model with input from lattice calculations, respectively [4]. The quoted errors indicate the sum of the statistical and systematic errors added in quadrature. Dashed lines represent the central value of the experiment. The square symbol shows the prediction of a lattice calculation for the 1S hyperfine splitting.

The mass and the width of the lowest lying charmonium state $\eta_c(1S)$, continue to have large uncertainties when compared to those other charmonium states [5]. The comparison between different experimental setups for the mass and width of $\eta_c$ is shown in Figure 2. All the measurements are classified in two different groups, radiative transitions (red circles) and other process, $\gamma\gamma$ or $p\bar{p}$ production (blue circles). The data are not internally consistent considering the large spread and their uncertainties. Part of the discrepancy could be due to the interpretation of the line shape of the reconstructed $\eta_c(1S)$ which were in many cases based on a simple Breit Wigner distribution due to limited statistics in the experiment.

3. Study of $\psi(3686) \rightarrow \gamma\eta_c(1S)$

Recently, the analysis of M1 radiative transition of $\psi(3686) \rightarrow \gamma\eta_c(1S)$ was studied in BESIII based on a $106 \times 10^6 \psi(3686)$ data sample. The $\eta_c(1S)$ mass and width are determined from fits to the invariant mass spectra of 6 exclusive decay modes of $\eta_c(1S)$: $K_SK^\pm\pi^\mp$, $K^\pm K^\mp\pi^0$, $\eta\pi^\pm\pi^\mp$, $K_SK^\pm\pi^\pm\pi^\mp\pi^\mp$, $K^\pm K^\mp\pi^\pm\pi^\mp\pi^0$ and $3(\pi^\pm\pi^\mp)$, where the $K_S$ is reconstructed in $\pi^+\pi^-$, and the $\eta$ and $\pi^0$ in $\gamma\gamma$ decays. The solid curves in Figure 3 show the results of an unbinned simultaneous maximum likelihood fit with three components: signal, non-resonant background, and a combined background consisting of $\pi^0X_i$ decays, continuum, and other $\psi(3686)$ decays. The mass and the width of $\eta_c(1S)$ were found to be $M = 2984.3 \pm 0.6 \pm 0.6$ MeV/$c^2$ and
Figure 2. Comparison between different experimental measurements of the mass and the width of the $\eta_c$. Red circles indicate the results of radiative transitions and the blue circles $\gamma\gamma$ or $p\bar{p}$ production results.

Figure 3. The $M(X_i)$ invariant mass distributions for the 6 exclusive decay modes of $\eta_c(1S)$. Points are data and the various curves are the total fit results. Signals are shown as short-dashed lines, the non-resonant components as long-dashed lines, and the interference between them as dotted lines. Shaded histograms (in red/yellow/green) are for (continuum/$\pi^0X_i$/other $\psi(3686)$ decays) backgrounds [6].

$\Gamma = 32.0 \pm 1.2 \pm 1.0$ MeV [6]. In this analysis, the $\eta_c(1S)$ line shapes are described successfully by using a combination of the energy dependence of the hindered-M1 transition matrix element and a full interference with non-resonant $\psi(3686)$ radiative decays. For the first time, an interference
between \( \eta_c(1S) \) and non-resonant background has been considered in \( \psi(3686) \to \gamma \eta_c(1S) \) analysis. The statistical significance of the interference was found to be 15\( \sigma \). This result confirms the previous CLEO-c observation of the line shape distortion [7], and may partly clarify the discrepancy found between older experiments, since the interference significantly affects the \( \eta_c(1S) \) mass and width and was not always considered.

There has been a long-standing puzzle on the radiative transition rates of \( \psi(3686) \to \gamma \eta_c(1S) \). The predicted partial decay width for \( \psi(3686) \to \gamma \eta_c(1S) \) was nearly one order of magnitude larger than the experimental data. Such discrepancies not seem to be trivial and have initiated a lot of theoretical interests in the literature [8]. Inspired by BESIII, it has been proposed [9] to consider the intermediate meson loop (IML) corrections as an unquenched mechanism in the charmonium energy region. Such a mechanism turns out to be important for exclusive transitions especially when the mass of the initial state is close to the open-charm threshold [10]. In Ref. [9], it was shown that the \( J/\psi \) exclusive decays would experience relatively smaller open-charm effects than the \( \psi(3686) \) since the latter is much closer to the \( DD \) threshold. In another word, the IML would have more important impact on the \( \psi(3686) \) decays, while the \( J/\psi \) suffers less. BES collaboration is going to measure the mass and width of \( \eta_c(1S) \) and branching fraction of \( \psi(3686) \to \gamma \eta_c(1S) \) using four times more statistic.

4. Study of \( J/\psi \to \gamma \eta_c(1S) \)

The \( J/\psi \to \gamma \eta_c(1S) \) decay is a M1 transition in charmonium with the most probable photon energy of about 114 MeV and a fairly large branching fraction of (1.7 \( \pm \) 0.4)% [11]. The Crystal Ball collaboration measured this branching fraction in the inclusive photon spectrum and obtained the value of (1.27\( \pm \)0.36)% [12]. There are a lot of theoretical predictions for this decay rate that are based upon QCD sum rules, lattice QCD calculations and so on, but as a rule they lead to values approximately twice as large as the Crystal Ball result. This discrepancy remained unchanged for more than twenty years. During this period no new measurements of this branching fraction were performed, and the PDG average was based on the single Crystal Ball result. Only in 2009 the CLEO Collaboration published the result of a new measurement [3], in which 12 exclusive decay modes of the \( \eta_c(1S) \) were analyzed. The obtained value \( B(J/\psi \to \gamma \eta_c(1S)) = (1.98 \pm 0.09 \pm 0.30)\% \) is closer to theoretical predictions. Combining the Crystal Ball and CLEO results, the PDG obtained \( B(J/\psi \to \gamma \eta_c(1S)) = (1.7 \pm 0.4)\% \) [1] with a scale factor of 1.6. Recently, a new direct measurement of the partial width of \( J/\psi \to \gamma \eta_c(1S) \) was performed by KEDR. In Figure 4 this result is compared with the Crystal Ball and CLEO measurements [13] (filled circles) as well as with theoretical predictions (open circles). This decay rate value is significantly higher compared to those experimental results, but is well consistent with the latest lattice QCD prediction [14]: \( \Gamma_{\eta_c}(1S) = (2.64 \pm 0.11) \) keV. BESIII will be able to do the direct measurement of this decay rate by using the largest data sample of \( J/\psi \). This is one the currently ongoing analysis at BESIII. The expected precision of the BESIII is indicated in Figure 4 as well.

5. Mass and width of the \( \eta_c(2S) \)

The decay of \( \psi(3686) \to \gamma \eta_c(2S) \) is experimentally challenging due to the low energy of the transition photon of about 50 MeV involved in this process. The branching fraction has been calculated by many authors, with predictions in the range \( B(\psi(3686) \to \gamma \eta_c(2S)) = (0.1 - 6.2) \times 10^{-4} \). Experimentally, this transition has been searched for by Crystal Ball and CLEO. No convincing signal was observed in any of these searches. Recently, the first observation of this M1 transition was done at BESIII through the decay processes \( \psi(3686) \to \gamma K_s K^+ \pi^- \) and \( \gamma K^+ K^- \pi^0 \) [15]. The branching fraction measurement of the M1 transition \( \psi(3686) \to \gamma \eta_c \) of (6.8 \( \pm \) 1.1 \( \pm \) 4.5) \( \times 10^{-4} \) agrees with theoretical calculations and naive estimates based on the \( J/\psi \to \gamma \eta_c \) transition [3]. The main systematic limitations to these measurements arise from the
choice of the functional form for the damping factor in the $\eta_c$ line shape and from uncertainty in the choice of the background line shapes. In this analysis, we were able to see the signal with $106 \times 10^6 \psi(3686)$ data sample. This analysis is ongoing with four times more statistics. With this large data sample of $\psi(3686)$, we will be able to measure the basic properties of $\eta_c(2S)$ more precisely which might help us in understanding the line shape features of the $\eta_c(1S)$ as well.

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