Charmonium Decays at BESIII

Meike Küßner,
on behalf of the BESIII collaboration
Institute for Experimental Physics I, Ruhr-University Bochum, Bochum, Germany
E-mail: mkuessner@ep1.ruhr-uni-bochum.de

Abstract. Although the charmonium spectrum seems to be well understood and was a role model on how theory and experiment worked hand in hand, the charmonium spectrum still rises questions. For states as $h_c$, $\chi_{cJ}$ and $\eta_c(2S)$, the majority of decay channels is still unknown. Since the charmonium states occur in the transition region of perturbative and non-perturbative QCD, theoretical predictions suffer from large uncertainties. Experimental challenges arise from limited statistics due to the production processes of non vector states. The BESIII collaboration studies extensively the charmonium spectrum and the decay behavior of charmonium states to shed light on the various questions. In this article recent results on charmonium decays studied by BESIII will be presented.

1. Introduction
1.1. The Charmonium Spectrum
Since the $J/\psi$ was discovered in 1974, the charmonium spectrum (s. Figure 1) has been established meanwhile. Below the open-charm threshold many states have been predicted and were confirmed experimentally soon after. Other states which are predicted, have not been found yet especially above the open-charm threshold. But also other states, especially exotic states were found in the charmonium sector without any prediction beforehand. Although masses and total widths of charmonium states have been widely measured with high precision, the decay behavior especially of states not carrying the quantum numbers $J^{PC}=1^{--}$ is still incomplete and lacking from precise theoretical predictions and measurements. While vector states can easily be studied in $e^+e^-$ annihilation in resonant production with high precision, the production of states that can only be accessed via transitions (e.g. $\chi_{cJ}$, $\eta_c h_c$) is limited by statistics due to small branching fractions which imposes an additional experimental challenge. Therefore the BESIII experiment plays a key role and offers a unique possibility to study these states due to high statistic data samples that were accumulated in the last decade.

Despite the success of Quantum Chromo Dynamics (QCD), the non-perturbative dynamics of the strong interaction are not fully understood yet. The high mass of the $c$ quark ($1.3$ GeV/$c^2$) allows theoretical approaches that are based on non-relativistic models that are corrected by relativistic terms such as spin-orbital and spin-spin contributions. As one looks higher at heavier charmonium states in mass these simplifications are not valid anymore. Therefore charmonium physics also offers a unique approach to probe strong interaction in the transition region of perturbative and non-perturbative QCD. Charmonium spectroscopy serves as an ideal tool to
shed light on the dynamics of the strong interaction such as generation of hadron masses, spin-spin and spin-orbital dependent contributions.

Figure 1. The spectrum of charmonium and charmoniumlike mesons [1].

1.2. General Remarks on Charmonium Decays
Since charmonium states below the open-charm threshold have limited possibilities to decay, OZI suppressed decays become competitive. Hence these states are rather narrow. Other decays often proceed via radiative- or hadronic transitions (s. Figure 2). Hadronic transitions proceed via the emission of soft gluons which therefore become non perturbative and thus suffer from limited predictions. Precision measurements of the mass and width of these charmonium spectrum give therefore access to the confinement potential in QCD. In addition, the various charmonium states with well-defined spin and parity serve as ideal systems to study via their decay modes the validity of perturbative QCD and to probe the light-quark sector as well. Above the open-charm threshold, decays into open-charm mesons dominate.

Although some general features are well known and the knowledge of the decay behavior of vector states is rather complete, this decay behavior of states like \( \eta_c \), \( \chi_{cJ} \), \( \eta_c(1S) \) and \( \eta_c(2S) \) is barely understood. Only 3% of the decay modes of the \( \eta_c(2S) \) are measured, 27% of the \( \chi_{c2} \), 40% of the \( \chi_{c1} \), 17% of the \( \chi_{c0} \) and 53% of the \( h_c \) [2].
Figure 2. Feynman diagrams of the main decay processes of charmonia. (a) radiative transition, (b) hadronic transition, (c) OZI suppressed decay.

1.3. BESIII at BEPCII

The BESIII (Beijing Spectrometer III) detector is located at the Beijing Electron Positron Collider II (BEPCII) at the Institute of High Energy Physics in Beijing, PRC. The third generation experiment operates in the so-called $\tau$-charm energy region at center of mass energies between $2.0 - 4.6$ GeV. The design luminosity of $\mathcal{L} = 10^{33}$ cm$^{-2}$s$^{-1}$ at the 3.77 GeV has been achieved in 2016. Since the start of data taking in 2008, the BESIII collaboration accumulated the world’s largest data samples at the $J/\psi$, $\psi'$ and $\psi(3770)$ energy. During the past years, BESIII has collected over 12 fb$^{-1}$ of data dedicated to XYZ studies between 4.18 and 4.6 GeV and more data yet to come. The BESIII detector design (s. Figure 3) follows the typical scheme of a typical onion shell-like central detector. The detector is divided into a barrel part and two endcaps which offer together an acceptance of 93% of $4\pi$. From the innermost placed Beryllium beam pipe outwards, the detector consists of a Helium-based central Main Drift Chamber, a Time-of-Flight (TOF) detector based on plastic scintillators, a CsI(Tl) electromagnetic calorimeter followed by a superconducting magnet providing a 1 Tesla magnetic field to the inside. Finally, Resistive Plate Chambers operate as Muon Detector in the return yoke of the magnet. More details can be found in [3].

Figure 3. Schematic drawing of the BESIII detector}

2. Highlights of Recent Results in Charmonium Decays at BESIII

In this section, I want to discuss a few of the highlights that were obtained within the last year by the BESIII collaboration. The efforts and studies of BESIII resulted in a variety of papers so far. Some of them will be discussed in more detail hereafter. For further results please refer to [11, 12] which discussions go beyond the space of this article.
2.1. First Observation of $h_c \to \text{hadrons}$

Since the observation of the $h_c$ in 2005 [4] mass and width have been measured quite precisely, whereas only few decay modes have been observed. Up to now there is still no conclusion whether hadronic decays, radiative transitions or hadronic transitions play the leading role. From the experimental point the $h_c$ comes along with additional challenges due to the low production rate via $\psi' \to \pi^0 h_c (\sim 8.6 \cdot 10^{-5})$ which limits statistics right from the beginning.

In a recent publication of the BESIII collaboration [5] new decay modes have been found for the first time using $(4.48 \pm 0.03) \cdot 10^8 \psi(3686)$ events. Five hadronic decay modes have been studied via the process $\psi' \to \pi^0 h_c$. Three of them, $h_c \to p\bar{p}\pi^+\pi^-$, $\pi^+\pi^-\pi^0$ and $2(\pi^+\pi^-)\pi^0$, are observed for the first time with significances of $7.4\sigma$, $4.6\sigma$ and $9.1\sigma$ (s. Figure 4), and their branching fractions are determined to be $(2.89 \pm 0.32 \pm 0.55) \cdot 10^{-3}$, $(1.60 \pm 0.40 \pm 0.32) \cdot 10^{-3}$, and $(7.44 \pm 0.94 \pm 1.52) \cdot 10^{-3}$, respectively, where the first uncertainties are statistical and the second systematic. No significant signal is observed for the other two decay modes, and the corresponding upper limits of the branching fractions are determined to be $\mathcal{B}(h_c \to 3(\pi^+\pi^-)\pi^0) < 8.7 \cdot 10^{-3}$ and $\mathcal{B}(h_c \to K^+K^-\pi^+\pi^-) < 5.8 \cdot 10^{-4}$ at the 90% confidence level.

![Figure 4. Recoiling mass spectrum of the $\pi^0$ in the decay chains $\psi(3686) \to \pi^0 h_c$ with $h_c \to p\bar{p}\pi^+\pi^-$ (I), $\pi^+\pi^-\pi^0$ (II), $2(\pi^+\pi^-)\pi^0$ (III), $3(\pi^+\pi^-)\pi^0$ (IV), and $K^+K^-\pi^+\pi^-$ (V). [5]](image)

2.2. Search for $h_c \to \pi^+\pi^- J/\psi$ via $\psi' \to \pi^+\pi^- J/\psi$ 

Hadronic transitions are expected to be suppressed due to the limited phasespace. Theoretical predictions strongly vary between different models ($\mathcal{B}(h_c \to \pi/\psi) \sim 0.05\% - 2\%$ [6, 7]) and experimental input is needed to constrain them. Here another experimental challenge comes due to large background form $\psi(3686) \to \eta J/\psi$ into play. Using $(4.48 \pm 0.03) \cdot 10^8 \psi(3686)$ events, the most stringent upper limit of $\mathcal{B}(h_c \to \pi\pi J/\psi) < 3.6 \cdot 10^{-3}$ (90%CL) has been carried out by the BESIII collaboration [8]. This result favors the prediction given in [6] and therefore adds important experimental input to this discrepancy.
2.3. Observation of OZI suppressed decays $\chi_{cJ} \rightarrow \omega \phi$

Also hadronic decay modes of the $\chi_{cJ}$ suffer from large theoretical uncertainties and are experimentally challenging. With respect to OZI suppressed decays (e.g. $\chi_{cJ} \rightarrow \omega, \phi\phi$), the branching fractions are expected to be much smaller for doubly OZI suppressed decays as $\chi_{cJ} \rightarrow \omega \phi$. In a recently published BESIII analysis, the doubly OZI suppressed decays $\chi_{cJ} \rightarrow \omega \phi$ have been studied via $\psi(3686) \rightarrow \gamma \chi_{cJ}$ [9]. In addition to the previously established $\chi_{c0} \rightarrow \omega \phi$, the first observation of $\chi_{c1} \rightarrow \omega \phi$ is reported in this paper, as well as strong evidence for the decay $\chi_{c2} \rightarrow \omega \phi$ [9]. The branching fractions are determined to be $B(\chi_{c0} \rightarrow \omega \phi) = (13.84 \pm 0.70 \pm 1.08) \cdot 10^{-5}$, $B(\chi_{c1} \rightarrow \omega \phi) = (2.80 \pm 0.32 \pm 0.30) \cdot 10^{-5}$ (12.3σ) and $B(\chi_{c2} \rightarrow \omega \phi) = (1.00 \pm 0.25 \pm 0.14) \cdot 10^{-5}$ (4.8σ) (s. Figure 5). These results exceed theoretical predictions by one order of magnitude [10] which might be explained by the argument that doubly OZI rule could be violated since $\omega$ and $\phi$ are not ideal mixture of the flavour SU(3) octet and singlet. This brings up more interesting questions which are interesting to investigate further in experiment as well as in theory.

![Figure 5. Simulataneous fit result in the $\omega \phi$ sidebands and the signal region (blue). The dots with error bars are data, the dotted lines represent the signal component and the long-dashed line is background normalized using the simultaneous fit to the $\omega \phi$ sideband components.][9]

References

[1] S. L. Olsen, Frontiers of Physics 10 (2015), DOI: 10.1007/s11467-014-0449-6
[2] M. Tanabashi et al. Review of Particle Physics, (Particle Data Group), Phys. Rev. D 98 3 030001 (2018), DOI: 10.1103/PhysRevD.98.030001
[3] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett 122 232002 (2019), arXiv: 1903.04695
[4] Rosner, J. L. et al. (CLEO Collaboration), Phys. Rev. Lett. 95 19 102003 (2005), DOI: 10.1103/PhysRevLett.95.102003
[5] Ablikim, M. et al. (BESIII Collaboration), Phys. Rev. D 99 7 072008 (2019), DOI: 10.1103/PhysRevD.99.072008
[6] Kuang, Yu-Ping et al., Phys. Rev. D 37 5 1210 (1988), DOI: 10.1103/PhysRevD.37.1210
[7] Ko, Pyungwo, Phys. Rev. D 52 3 1710 (1995), DOI: 10.1103/PhysRevD.52.1710
[8] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 97 052008 (2018), DOI: 10.1103/PhysRevD.97.052008
[9] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 99 1 012015 (2019), DOI: 10.1103/PhysRevD.99.012015
[10] D. Y. Chen et al., Phys. Rev. D 81 7 074006 (2010), DOI: 10.1103/PhysRevD.81.074006
[11] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 98 3 032006 (2018), DOI: 10.1103/PhysRevD.98.032006
[12] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 99 3 032006 (2009), DOI: 10.1103/PhysRevD.99.032006