Progress in light hadron spectroscopy at BESIII

W C Yan (on behalf of BESIII Collaboration)
University of Science and Technology of China, Hefei, Anhui, 230026, China.
E-mail: wencheng@mail.ustc.edu.cn

Abstract. Using samples of $1.31 \times 10^9 \ J/\psi$ events and $1.06 \times 10^8 \ \psi(3686)$ events accumulated at the BESIII detector, the recent progresses in the light meson spectroscopy and baryon spectroscopy are presented.

1. Introduction
Most of the hadronic states could be properly understood in the framework of constituent quark model [1], which is very successful in describing the observed spectrum, especially for the heavy flavor sector. However, the situation is quite different for the light hadronic spectrum. That is due to the large effective coupling within Quantum Chromo Dynamics (QCD) in the low energy regime, and the perturbative theory becomes invalid. Therefore, light hadron spectroscopy from the experimental measurement is a unique way to understand and verify the QCD formalism. In addition, QCD also predicts some new exotic hadrons, e.g. glueballs, multiquark states and hybrids. It has been the aim for many years to search for exotic states: many candidates have been reported, but none of them is unambiguously established yet.

The $J/\psi$ and $\psi(3686)$ decays, especially the radiative decays, can provide wealthy information on the light hadron spectroscopy. Since their masses are below the mass threshold of charmed meson pair, the direct decay into charmed mesons is forbidden, which offers an excellent laboratory to study light hadron spectroscopy.

The BESIII detector [2] is a general-purpose magnetic spectrometer operating at BEPCII [3], which is a double-ring $e^+e^-$ collider with the center-of-mass energy energy between 2.0 and 4.6 GeV. In 2009, samples of $2.25 \times 10^8 \ J/\psi$ events and $1.06 \times 10^8 \ \psi(3686)$ events were collected with the BESIII detector. To study the light hadron physics comprehensively, in 2012, more data samples of $J/\psi$ and $\psi(3686)$ with a factor 4 of events number were accumulated, and $1.31 \times 10^9 \ J/\psi$ events and $4.48 \times 10^8 \ \psi(3686)$ events have been totally collected with the BESIII detector. In this talk, we present the recent progresses in light meson spectroscopy and baryon spectroscopy at BESIII.

2. Light meson spectroscopy
For the light meson spectroscopy, the attention will be focused on the observed $X(18xx)$ states and $f_2^0$ states in $J/\psi$ radiative decays.

2.1. $X(18xx)$ States
A strong $p\bar{p}$ mass threshold enhancement, namely $X(p\bar{p})$, was firstly observed by the BESII experiment in $J/\psi \to \gamma p\bar{p}$ [4], and later confirmed by the CLEO-c [5] and BESIII [6]. Based
on the $2.25 \times 10^8 J/\psi$ events accumulated at the BESIII detector, a Partial Wave Analysis (PWA) of $J/\psi \rightarrow \gamma pp$ [7] is performed, in which the effect of final state interaction (FSI) is considered by using the Jülich formulation [8]. In the optimal PWA fit, as shown in Fig. 1 (a), the $J^{PC}$ of the $X(pp)$ is assigned to be $0^{-+}$, and the statistical significance of the $X(pp)$ component is much larger than 30$\sigma$. The mass and width are determined to be $M = 1832^{+0}_{-10} (\text{stat})^{+10}_{-15} (\text{syst}) \pm 19$ (model) MeV/$c^2$, $\Gamma = 13 \pm 39 (\text{stat})^{+13}_{-13} (\text{syst}) \pm 4$ (model) MeV/$c^2$ (a total width of $\Gamma < 76$ MeV/$c^2$ at the 90% confidence level), respectively.

A new resonance, $X(1835)$, was observed in $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ [9] at the BESIII, which was confirmed via the same decay channel by the BESIII experiment [10]. At present, the $X(1835)$ is further confirmed in a PWA of $J/\psi \rightarrow \gamma K^0_SK^0_S\eta$ with the sample of $1.31 \times 10^9 J/\psi$ events [11]. The PWA is performed to the events satisfying $M(K^0_SK^0_S\eta) < 2.8$ GeV/$c^2$ and $M(K^0_SK^0_S) < 1.1$ GeV/$c^2$. The PWA fit, as shown in Fig. 1 (b), requires a contribution from $X(1835) \rightarrow K^0_SK^0_S\eta$ with a statistical significance greater than 12.9$\sigma$, and the spin parity of the $X(1835)$ is determined to be $0^{-+}$. The mass and width of the $X(1835)$ are measured to be $M = 1844 \pm 9 (\text{stat})^{+16}_{-20} (\text{syst})$ MeV/$c^2$ and $\Gamma = 192^{+20}_{-12} (\text{stat})^{+62}_{-45} (\text{syst})$ MeV/$c^2$, respectively. The mass and width of the $X(1835)$ are consistent with the values obtained from the decay $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$.

A strong deviation from the doubly OZI suppressed decay $J/\psi \rightarrow \omega\phi$ is observed near the $\omega\phi$ mass threshold [12] using the sample of $2.25 \times 10^8 J/\psi$ events. Assuming the enhancement is due to the $X(1810)$ resonance, the PWA with a tensor covariant amplitude determine that the spin parity of the $X(1810)$ is $0^{++}$, and the statistical significance is more than 30$\sigma$, as shown in Fig. 1 (c). The mass and width of the $X(1810)$ are determined to be $M = 1975 \pm 7 (\text{stat})^{+13}_{-5} (\text{syst}) \pm 19$ (model) MeV/$c^2$ and $\Gamma = 95 \pm 10 (\text{stat})^{+21}_{-34} (\text{syst}) \pm 75$ (model) MeV/$c^2$, respectively.

**Figure 1.** (a) The $X(pp)$ invariant-mass spectrum in $J/\psi \rightarrow \gamma pp$, (b) the $X(1835)$ in the $K^0_SK^0_S\eta$ invariant-mass spectrum in $J/\psi \rightarrow \gamma K^0_SK^0_S\eta$, (c) the $X(1810)$ in the $K^+K^-\pi^+\pi^-\pi^0$ invariant-mass spectrum in $J/\psi \rightarrow \gamma \omega\phi$.

In addition, two new structures around 1.85 GeV/$c^2$ are also observed in the other $J/\psi$ decays based on the sample of $2.25 \times 10^8 J/\psi$ events. One is $X(1840)$ in the $3(\pi^+\pi^-)$ mass spectrum of $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$ [13] with a statistical significance of 7.6$\sigma$, as shown in Fig. 2 (a). The mass and width are measured to be $M = 1842.2 \pm 4.2 (\text{stat})^{+7.1}_{-2.6} (\text{syst})$ MeV/$c^2$ and $\Gamma = 83 \pm 14 (\text{stat}) \pm 11 (\text{syst})$ MeV/$c^2$, respectively. The other is $X(1870)$ in the decay of $J/\psi \rightarrow \omega\phi\pi^-\eta$ [14], which is firstly observed at the BESIII experiment with the statistical significance of 7.2$\sigma$. From the fit, as shown in Fig. 2 (b), the mass and width are determined to be $M = 1877.3 \pm 6.3 (\text{stat})^{+3.4}_{-7.3} (\text{syst})$ MeV/$c^2$ and $\Gamma = 57 \pm 12 (\text{stat})^{+10}_{-4} (\text{syst})$ MeV/$c^2$, respectively. The spin parities of these two structures are still unknown.

The BESIII results of the masses and widths of the $X(pp)$, $X(1835)$, $X(1810)$, $X(1840)$ and
X(1870) are compared in Fig. 2 (c). The X(p̅p) and X(1835) have the same J^P_C = 0^{−+}, similar central mass but different widths, and there is a speculation that the X(p̅p) may be the tail of the X(1835). The X(1810) is not compatible with either the X(1835) or the X(p̅p) due to the different masses and spin parities. The mass of the X(1840) is consistent with the X(p̅p) and X(1835), but the width is significantly different from either of them, and much smaller than the width of the X(1835). While for the X(1870), whether it is due to the X(1835) or the η(2170), an interference of both, or a new resonance, it still needs further study.

Figure 2. (a) The X(1840) in the 3(π^+π^-) invariant-mass spectrum in J/ψ → γ3(π^+π^-), (b) the X(1870) in the π^+π^-η invariant-mass spectrum in J/ψ → ωπ^+π^-η, (c) the comparisons of the observed X(18xx) states at the BESIII.

2.2. f_2^+ states
A full PWA on the radiative decay of J/ψ → γηη is performed using the relativistic covariant tensor amplitude method based on the sample of 2.25 \times 10^8 J/ψ events [15]. The PWA results, listed in Tab. 1, show that the dominant scalar components are from the f_0(1500), f_0(1710) and f_0(2100), while no evident contributions from f_0(1370) or f_0(1790) are observed. The tensor components, which are dominantly from f_2(1525), f_2(1810) and f_2(2340), also have a large contribution in J/ψ → γηη.

Table 1. Summary of the PWA results of J/ψ → γηη, including the masses and widths with uncertainties, branching ratios, as well as the significance. The first errors are statistical and the second are systematic.

| Resonance | Mass(MeV/c^2) | Width(MeV/c^2) | B(J/ψ → γX → γηη) | Significance |
|-----------|--------------|----------------|-------------------|--------------|
| f_0(1500) | 1468±14±24   | 130±20±4      | (1.65±0.26±0.31)×10^{-5} | 2.9σ         |
| f_0(1710) | 1759±6±25    | 172±4±16      | (2.35±0.11±0.74)×10^{-4} | 25.0σ        |
| f_0(2100) | 2081±13±36   | 273±7±70      | (1.13±0.10±0.64)×10^{-3} | 3.0σ         |
| f_2(1525) | 1513±5±10    | 75±12±16      | (3.42±0.33±1.37)×10^{-5} | 11.0σ        |
| f_2(1810) | 1822±9±16    | 229±10±18     | (5.40±0.60±3.32)×10^{-5} | 6.4σ         |
| f_2(2340) | 2362±31±57   | 334±54±100    | (5.60±0.65±2.07)×10^{-5} | 7.6σ         |

Another model-independent PWA is performed on the radiative decay of J/ψ → γπ^0π^0 with the sample of 1.31 \times 10^8 J/ψ events [16]. The goal of this analysis is to provide a description of the scalar and tensor components of the π^0(π^0) system while making minimal assumptions about the properties or number of poles in the amplitude. The PWA results indicate that the scalar contributions are mainly from σ(600), f_0(1370), f_0(1500), f_0(1710) and f_0(2020). The tensor components are from the dominant contribution of f_2(1270).
3. Baryon spectroscopy
For the baryon spectroscopy, we only report the observed excited \( N^* \) states and two hyperons at the BESIII experiment.

3.1. Excited \( N^* \) states
To search for new excited \( N^* \) baryons, a PWA of \( \psi(3686) \rightarrow p\bar{p}\pi^0 \) is performed based on \( 1.06 \times 10^8 \psi(3686) \) events [17]. In this PWA, seven \( N^* \) intermediate resonances are observed. Besides the five established resonances, \( N(1440) \), \( N(1520) \), \( N(1535) \), \( N(1650) \) and \( N(1720) \), two new resonances, \( N(2300) \) and \( N(2570) \), are also observed with the statistical significance both higher than \( 11\sigma \). The optimized results of the PWA for the seven \( N^* \) states are listed in Tab. 2.

Table 2. The optimized mass, width and significance of the seven significant \( N^* \) resonances. \( \Delta S \) and \( \Delta N_{\text{ dof}} \) represent the change of the log likelihood value and the change of the number of free parameters in the fit, respectively. In the second and third columns, the first uncertainty is statistical and the second systematic.

| Resonance  | Mass(\( \text{MeV}/c^2 \)) | Width(\( \text{MeV}/c^2 \)) | \( \Delta S \) | \( \Delta N_{\text{ dof}} \) | Significance |
|------------|-----------------------------|-------------------------------|----------------|-----------------------------|-------------|
| \( N(1440) \) | \( 1390^{+14+21}_{-21-30} \) | \( 340^{+46+10}_{-40-156} \) | 72.5 | 4 | 11.5\( \sigma \) |
| \( N(1520) \) | \( 1510^{+3+11}_{-7-9} \) | \( 115^{+20+10}_{-18-40} \) | 19.8 | 6 | 5.0\( \sigma \) |
| \( N(1535) \) | \( 1535^{+9+15}_{-8-22} \) | \( 120^{+20+10}_{-18-42} \) | 49.4 | 4 | 9.3\( \sigma \) |
| \( N(1650) \) | \( 1650^{+5+30}_{-5-30} \) | \( 150^{+21+14}_{-22-50} \) | 82.1 | 4 | 12.2\( \sigma \) |
| \( N(1720) \) | \( 1700^{+30+32}_{-28-35} \) | \( 450^{+100+149}_{-94-44} \) | 55.6 | 6 | 9.6\( \sigma \) |
| \( N(2300) \) | \( 2300^{+40+109}_{-30-0} \) | \( 340^{+30+110}_{-30-58} \) | \( 120.7 \) | 4 | 15.0\( \sigma \) |
| \( N(2570) \) | \( 2570^{+10+10}_{-19+34} \) | \( 250^{+24-21}_{-24-21} \) | 78.9 | 6 | 11.7\( \sigma \) |

3.2. Excited hyperons states
Using a sample of \( 1.06 \times 10^8 \psi(3686) \) events collected with the BESIII detector, the processes of \( \psi(3686) \rightarrow K^-\Lambda \Xi^+ + \text{c.c.} \) and \( \psi(3686) \rightarrow \gamma K^-\Lambda \Xi^+ + \text{c.c.} \) are studied for the first time [18]. In the decay \( \psi(3686) \rightarrow K^-\Lambda \Xi^+ + \text{c.c.} \), two new hyperons, \( \Xi(1690)^- \) and \( \Xi(1820)^- \) shown in Fig. 3, are confirmed in \( K^-\Lambda \) mass spectrum with the statistical significance of 4.9\( \sigma \) and 6.9\( \sigma \), respectively. The masses and widths of the \( \Xi(1690)^- \) and \( \Xi(1820)^- \) are measured to be \( M_{\Xi(1690)^-} = 1687.7 \pm 3.8 \) (stat) \( \pm 1.0 \) (syst) \( \text{MeV}/c^2 \), \( \Gamma_{\Xi(1690)^-} = 27.1 \pm 10 \) (stat) \( \pm 2.7 \) (syst) \( \text{MeV}/c^2 \), and \( M_{\Xi(1820)^-} = 1826.7 \pm 5.5 \) (stat) \( \pm 1.6 \) (syst) \( \text{MeV}/c^2 \), \( \Gamma_{\Xi(1820)^-} = 54.4 \pm 15.7 \) (stat) \( \pm 4.2 \) (syst) \( \text{MeV}/c^2 \), which are consistent with the values from PDG [19] within one standard deviation.

![Figure 3. The hyperons \( \Xi(1690)^- \) and \( \Xi(1820)^- \) in \( K^-\Lambda \) invariant mass spectrum.](image)
In the decay $\psi(3686) \rightarrow \gamma K^- \Lambda \Xi^+ + \text{c.c.}$, the measured branching fractions are summarized in Tab. 3. The measurements provide new information on charmonium decays to hyperons and on the resonance parameters of the hyperons, and may help in the understanding of the charmonium decay mechanism.

**Table 3.** Summary of the branching fractions measurements in the decay $\psi(3686) \rightarrow \gamma K^- \Lambda \Xi^+ + \text{c.c.}$, where the first uncertainty is statistical and the second systematic.

| Decay                                               | Branching fraction $B$             |
|-----------------------------------------------------|-----------------------------------|
| $\psi(3686) \rightarrow K^- \Lambda \Xi^+$          | $(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$ |
| $\psi(3686) \rightarrow \Xi(1690)^- \Xi^+$, $\Xi(1690)^- \rightarrow K^- \Lambda$ | $(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$ |
| $\psi(3686) \rightarrow \Xi(1820)^- \Xi^+$, $\Xi(1820)^- \rightarrow K^- \Lambda$ | $(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$ |
| $\psi(3686) \rightarrow K^- \Sigma^0 \Xi^+$         | $(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$ |
| $\psi(3686) \rightarrow \gamma \chi_{c0}$, $\chi_{c0} \rightarrow K^- \Lambda \Xi^+$ | $(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$ |
| $\psi(3686) \rightarrow \gamma \chi_{c1}$, $\chi_{c1} \rightarrow K^- \Lambda \Xi^+$ | $(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$ |
| $\psi(3686) \rightarrow \gamma \chi_{c2}$, $\chi_{c2} \rightarrow K^- \Lambda \Xi^+$ | $(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$ |

4. Summary

Based on the data samples of $J/\psi$ and $\psi(3686)$ accumulated at the BESIII detector, the recent progresses in the light meson spectroscopy and baryon spectroscopy are presented. For the light meson spectroscopy, the observed $X(18xx)$ states near the $p\bar{p}$ mass threshold are reviewed. In addition, the $f_J^p$ states in the PWA of $J/\psi \rightarrow \gamma \eta \eta$ and $J/\psi \rightarrow \gamma \pi^0 \pi^0$ are reported. For the baryon spectroscopy, two new resonances, $N(2100)$, $N(2200)$, are observed for the first time, and two hyperons, $\Xi(1690)^-$ and $\Xi(1820)^-$, are firstly observed in charmonium decay.

The $J/\psi$ and $\psi(3686)$ decays, especially the radiative decays, have been used extensively for the study of the light hadron spectroscopy at the BESIII experiment. With the high statistics data accumulated at the BESIII detector, more interesting results are expected to be coming soon.

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