PROCEEDINGS OF SCIENCE

# Light meson spectroscopy at BESIII

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Light meson spectroscopy plays an important role in understanding the Quantum Chromodynamics in non-perturbative energy region and the decay dynamics of unconventional hadronic states. BESIII has collected the largest $J/\psi$ and $\psi'$ data samples in the world, which provides an unprecedented opportunity to study the light meson spectroscopy. The paper presents some highlights on light meson spectroscopy achieved in BESIII, such as search for glueball candidates, studies of the structure near $p\bar{p}$ threshold and studies of strange quarkonium.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

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PoS(PANIC2021)186

## 1. Introduction

Confinement is a unique property of Quantum Chromodynamics (QCD). The non-Abelian property of QCD permits the existence of bound states beyond conventional mesons and baryons, such as glueballs, hybrid states, and multiquark states. The identification and systematic study of these states would provide critical information for understanding the confinement. Searching for these unconventional states is one of the main interests in experimental particle physics. Data with unprecedented statistical accuracy, excellent detector performance and clearly defined initial and final states properties resulted in significant advances in recent years, and offer great opportunities to investigate meson spectroscopy at BESIII.

## 2. Glueballs

Lattice QCD (LQCD) predicts that the lowest-lying glueball states should occur in 1.5-1.7 GeV/$c^2$ with $J^{PC} = 0^{++}$. The next-higher glueball states have conventional quantum numbers, $2^{++}$ (mass 2.3-2.4 GeV/$c^2$) and $0^{-+}$ (mass 2.3-2.6 GeV/$c^2$), and hence are mixed with the conventional meson spectrum making them difficult to be identified experimentally. Glueballs identification require systematic studies based on the search of outnumbering of conventional quark model states. Charmonium radiative decays provide a gluon-rich environment and are regarded as one of the most promising hunting grounds for gluonic excitations.

### 2.1 Searching for scalar glueball

The most striking observation is that $f_0(1500)$ and $f_0(1710)$ appear to be supernumerary. Many papers interpret the existence of these scalars as a manifestation of the underlying light quarkonium nonet and the low lying scalar glueball. Therefore the production mechanisms and decay rates are needed to unravel the quark content of $f_0(1500)$ and $f_0(1710)$. Several measurements are discussed here based on a sample of $1.31 \times 10^9$ $J/\psi$ events collected at BESIII. The mass independent amplitude analysis of $J/\psi \to \gamma\pi^0\pi^0$ shows that the contributions around 1.5 GeV and 1.7 GeV are scalar states [1]. The partial wave analysis (PWA) of $J/\psi \to \gamma\eta\eta$ [2] and $J/\psi \to \gamma K_s K_s$ [3] are also performed at BESIII, the branching fractions of the $f_0(1710)$ are one order of magnitude larger than those of the $f_0(1500)$. And the known branching fraction of $J/\psi \to \gamma f_0(1710)$ is summed up to $1.7 \times 10^{-3}$ [4], which is comparable to the LQCD calculation of scalar glueball ($3.8 \times 10^{-3}$). The production property suggests $f_0(1710)$ has larger gluonic component than $f_0(1500)$.

### 2.2 Searching for tensor glueball

The tensor sector is extremely busy and a large number of tensor states appear in the Particle Data Group (PDG). The large production rate of the $f_2(2340)$ in $J/\psi \to \gamma\phi\phi$ [5] and $J/\psi \to \gamma\eta\eta$ [2] indicates $f_2(2340)$ is a good candidate of tensor glueball. Significant tensor contribution around 2.4 GeV/$c^2$ also presents in $J/\psi \to \gamma K_s K_s$, assigned as $f_2(2370)$. However, the measured production rate of $f_2(2370)$ appears to be substantially lower than the LQCD prediction.It is desirable to search for more decay modes to establish and characterize the lowest tensor glueball.

### 2.3 Searching for pseudoscalar glueball

A possible pseudoscalar glueball candidate, $X(2370)$, was first observed in $J/\psi \to \gamma\pi^+\pi^-\eta^{'}$ [6], with the statistic significance of 6.4 $\sigma$. The measured mass of the $X(2370)$ is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation. Based on chiral effective Lagrangian and under the assumption of glueball, the branching fractions of $X(2370)$ decaying into $\eta\eta\eta^{'}$, $KK\eta^{'}$ and $\pi\pi\eta^{'}$ are predicted to be 0.00082, 0.011 and 0.090, respectively [7].

Based on a sample of $1.31 \times 10^9$ $J/\psi$ events collected with the BESIII detector, $X(2370)$ is observed in $J/\psi \to \gamma K\bar{K}\eta^{'}$ with a statistical significance of 8.3 $\sigma$ [8]. The mass and width are determined to be $M = 2341.6 \pm 6.5(stat.) \pm 5.7(syst.)$ MeV/$c^2$ and $\Gamma = 117 \pm 10(stat.) \pm 8(syst.)$ MeV, which are consistent with BESIII previous measurements [9]. In order to demonstrate the above theoretical hypothesis, the decays of $J/\psi \to \gamma\eta\eta\eta^{'}$ are investigated by using the two $\eta^{'}$ decay modes, $\eta^{'} \to \gamma\pi^+\pi^-$ and $\eta^{'} \to \pi^+\pi^-\eta$. However, no evident signal for the $X(2370)$ is observed in the $\eta\eta\eta^{'}$ invariant mass distribution [10]. The upper limit of $B(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta^{'})$ is estimated to be $9.2 \times 10^{-6}$, which is not in contradiction with the prediction in Ref. [11]. To understand the nature of $X(2370)$, it is mandatory to measure its spin and parity and to search for it in more decay modes with 10 billion of $J/\psi$.

## 3. The structure near $p\bar{p}$ threshold

An anomalously strong enhancement at the proton-antiproton mass threshold was first observed by BES in $J/\psi \to \gamma p\bar{p}$ decays [12]. This enhancement was subsequently determined to have spin-parity $J^{PC} = 0^{-+}$ by BESIII [13]. The $X(1835)$ was first observed in $J/\psi \to \gamma\pi^+\pi^-\eta^{'}$ [14], and it was also observed in PWA of the $J/\psi \to \gamma K_s K_s \eta$, and its spin-parity was determined to be $J^{PC} = 0^-$ [15]. Recent BESIII studies based on about 1.3 billion $J/\psi$ decay events suggest that X(1835) could be either a $p\bar{p}$ molecule-like state or a $p\bar{p}$ bound state [16].

Using a sample of 1.3 billion $J/\psi$ events, two resonances were observed in $J/\psi \to \gamma\gamma\phi$ at BESIII [17], whose masses and widths are close to $\eta(1475)$ and $X(1835)$. According to angular distribution, the $J^{PC}$ around 1.4 GeV/$c^2$ and 1.8 GeV/$c^2$ tends to be $0^{-+}$. $J/\psi \to \gamma X$, $X \to \gamma V$ (where $V$ stands for $\rho, \phi, \omega$) is a flavor filter process, which provides information of quark content for X resonance. The observation of $\eta(1475)$ and $X(1835)$ in $\gamma\phi$ mass spectrum indicates that both $\eta(1475)$ and $X(1835)$ contain a sizable $s\bar{s}$ component.

Based on a sample of $1.31 \times 10^9$ $J/\psi$ events collected with the BESIII detector, $J/\psi \to \omega\pi^+\pi^-\eta^{'}$ is also studied [18]. No significant $X(1835)$ signal is observed in the $\pi^+\pi^-\eta^{'}$ invariant mass spectrum. The upper limit of the branching fraction is determined to be $B(J/\psi \to \omega X(1835)$ ,$X(1835) \to \omega\pi^+\pi^-\eta^{'})$<$6.2 \times 10^{-5}$ at 90% confidence level. Further investigations of $X(1835)$ in additional hadronic decay modes are needed.

## 4. Strange quarkonium($s\bar{s}$)

The study of the strangeonium mesons is a bridge between the light $u$, $d$ quarks and the heavy $c$, $b$ quarks. It provides information on non-perturbative QCD in the low energy region. In addition, the strangeonium spectrum also helps to identify the exotics. However, the strangeonium spectrum is much less well understood, and only a few states have been established. Therefore, it is necessary to search for missing states predicted by the relativistic quark model to improve the knowledge of the strangeonium spectrum.

A PWA of the decay $J/\psi \to K^+K^-\pi^0$ were performed by using a sample of $223.7 \times 10^6$ $J/\psi$ events [19]. The $K_2^*(1980)^\pm$ and the $K_4^*(2045)^\pm$ were first observed in $J/\psi$ decays. Two broad $1^{--}$ structures were observed in $K^+K^-$ mass spectrum, possibly contributed from $\omega(1650)$ and $\rho(2150)$.

Using a sample of $448.1 \times 10^6$ $\psi(3686)$ events, a PWA of $\psi(3686 \to K^+K^-\eta)$ was performed [20]. The simultaneous observation of the $\phi(1680)$ and $X(1750)$ indicates that the $X(1750)$ is distinct from the $\phi(1680)$. The possible candidate around 2.2 GeV/$c^2$ is either the $\phi(2170)$, $\rho(2150)$ or a superposition of both. However, it is still difficult to distinguish these states from the excited $\phi$ and $\rho$ states due to the limited statistics. Therefore, the combine analysis with other channels is needed.

## 5. Summary

Some highlights on the light meson spectroscopy at BESIII are presented in this talk. It consists of three parts, glueball, structure near the $p\bar{p}$ threshold, strangeonium. BESIII has already collected 10 billions $J/\psi$ data samples and is going to run for another ten more years. The data with unprecedented high-statistical accuracy will provide great opportunities to map out light meson spectroscopy and study QCD exotics. More fascinating results of light meson spectroscopy from BESIII are expected in future.

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