# Light Hadron Spectroscopy at BESIII

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**Abstract.** With data of 1.3 billion $J/\psi$ events and 106 million $\psi(2S)$ events collected with the BESIII detector operating at the BEPCII, many different analyses were performed. New baryon states were observed in partial wave analyses of charmonium decays. A comparison between the branching fraction of $\mathcal{B}(J/\psi \to \gamma f_0(1710))$ to the recent lattice QCD prediction of $J/\psi$ decaying to glueball ground state $\mathcal{B}(J/\psi \to \gamma G(0^{++}))$ benefits from new results of $J/\psi \to \gamma\eta\eta$. The observation of $\eta' \to \pi^+\pi^-\pi^+(\pi^0)\pi^-(\pi^0)$ via the radiative decay of $J/\psi \to \gamma\eta'$ agrees with the combined model of chiral perturbation theory and vector-meson dominance approach.

## 1. Introduction

Rich quantum states are allowed within the quantum chromodynamics (QCD) theory. However, glue-balls still remain unknown in experiments due to the difficult separation from light mesons. $J/\psi$ radiative decay providing a very clean laboratory of scalar and tensor glueballs, has long been used for hunting for glueballs. The Crystal Ball Collaboration [1] made the first observation of $f_0(1710)$ via $J/\psi \to \gamma\eta\eta$, but suffered from low statistics. Recent lattice QCD calculations [2, 3] tell that, the mass of glueball ground state with $J^{PC} = 0^{++}$ lies in the region of 1.5 to 1.7 GeV/$c^2$, and the branching fraction of $J/\psi \to \gamma G(0^{++})$ has a value of $3.8 \times 10^{-3}$. An comparison could be made by summing up branching fractions of $J/\psi \to \gamma f_0(1710) \to \gamma K^+K^-(\gamma\omega\omega, \gamma\pi\pi)$ and the new measurement of $J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta$. Another problem known as the "missing baryons" [4, 5] can be further understood by investigating new baryon states beyond fixed target experiments [6, 7, 8], because charmonium decays produced at the BESIII experiment take advantages of 93% acceptance of $4\pi$ coverage and high statistics to search for the missing baryons [9] [10] [11, 12]. $\eta'$ meson interpreted as a singlet state arising due to the axial $U(1)$ anomaly [13, 14], still remains active in theoretical studies aiming at extensions of chiral perturbation theory [17], from its discovery in 1964 [15, 16]. New insight could be made by the four-pion decays of $\eta' \to \pi^+\pi^-\pi^{+(0)}\pi^{-(0)}$, which could be mediated by the pentagon anomaly instead of suppression according to approximate symmetries. In experiment, no observation of the four-pion decays has been made only the best upper limits reported by the CLEO collaboration: $\mathcal{B}_1(\eta' \to \pi^+\pi^-\pi^+\pi^-) < 2.4 \times 10^{-4}$ and $\mathcal{B}_2(\eta' \to \pi^+\pi^-\pi^0\pi^0) < 2.6 \times 10^{-3}$ at the 90% confidence level (C.L.) [18] excluding the branching ratio of $1.0 \times 10^{-3}$ calculated using the broken-$SU_6 \times O_3$ quark model [19] three decades ago. Recent predictions $\mathcal{B}_1 = (1.0 \pm 0.3) \times 10^{-4}$ and $\mathcal{B}_2 = (2.4 \pm 0.7) \times 10^{-4}$ employed a combined model of chiral perturbation theory (ChPT) and a vector-meson dominance (VMD) approach [20].

In this paper, the results of partial wave analysis (PWA) on $J/\psi \to \gamma\eta\eta$ are presented based on a sample of 225 million $J/\psi$ events [21]. The PWA of the decay $\psi(2S) \to p\bar{p}\pi^0$ is performed using the 106 million $\psi(2S)$ events. The first observation of $\eta' \to \pi^+\pi^-\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\pi^0\pi^0$ takes advantage of $J/\psi \to \gamma\eta'$ decay with data of $1.3\times10^9$ $J/\psi$ events ($2.25\times10^8$ events in 2009 and $1.09\times10^9$ events in 2012) collected at the center of mass energy of 3.097 GeV with the BESIII detector [22].

The BESIII detector is a general-purpose spectrometer located at the Beijing Electron Position Collider (BEPCII) [23], designed with a double-ring $e^+e^-$ collider structure. The designed peak luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$ is optimized at the center of mass energy of 3.773 GeV. The cylindrical core of the BESIII detector consists of a helium-based main drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T (0.9 T in 2012) magnetic field. The acceptance of charged particles and photons has 93% over $4\pi$ coverage. The charged-particle momentum resolution at 1 GeV/$c$ is 0.5%, and the $dE/dx$ resolution is 6%. The photon energy resolution is 2.5% (5%) at 1GeV in the barrel (endcaps). The time resolution of TOF is 80 ps for the barrel and 110 ps for the end caps.

## 2. Partial wave analysis of $J/\psi \to \gamma\eta\eta$

This analysis[24] was performed using the relativistic covariant tensor amplitude method. The resonance parameters and branching fractions are listed in Table 1. Projections shown in Fig. 1 indicate that the dominant $0^{++}$ and $2^{++}$ components are from the $f_0(1710)$, $f_0(2100)$, $f_0(1500)$, $f_2'(1525)$, $f_2(1810)$ and $f_2(2340)$. Among all scalar components, the measured properties of dominant $f_0(1710)$ are consistent with results of $J/\psi \to \gamma K\bar{K}$ [25] and $J/\psi \to \gamma\pi\pi$ [26] at BESII. The production rate for the $f_0(1500)$ is lower than the one for $f_0(1710)$ and $f_0(2100)$ by almost one order. The first experimental evidence for the $f_0(1790)$ was observed in $J/\psi \to \phi\pi\pi$ but no evidence was observed in $J/\psi \to \phi K\bar{K}$ [27]. Tensor components, shown as the histogram in Fig. 1 (i), stand for their total contribution, where the peak component around 1.5 GeV/$c^2$ is the well-established resonance $f_2'(1525)$ and the components contributing to the bump around 2.1 GeV/$c^2$ are from $f_2(1810)$ and $f_2(2340)$. A tensor component around 1.8 GeV/$c^2$ with a statistical significance of $6.4\sigma$ exists and can not be distinguished from $f_2(1810)$, $f_2(1910)$ and $f_2(1950)$ with the present statistics, denoted as $f_2(1810)$ in this analysis, and the ambiguous assignment of $f_2(1810)$ or $f_2(1950)$ is considered as a source of systematic error. Other possible tensor resonances, $f_2(2010)$, $f_2(2150)$, $f_J(2220)$, $f_2(2300)$ and $f_2(2340)$, are also considered in alternative combinations to get the optimized solution. The best fit favors the presence of $f_2(2340)$. Since the mass of $f_2(2300)$ is close to $f_2(2340)$, an attempt was made by replacing $f_2(2340)$ with $f_2(2300)$ using the fixed mass and width referenced to PDG [28], and the log likelihood value gets worse by 15. The narrow $f_J(2220)$ (also known as $\xi(2230)$) reported by MarkIII [29] and BES [30] shows no evidence in this analysis. Component $f_J(2220)$ has a significance of $0.4\sigma$. None of the other contributions from scalar mesons, $f_0(1370)$, $f_0(2020)$, $f_0(2200)$ and $f_0(2330)$, have a significance greater than $5.0\sigma$, thus they are excluded.

**Table 1.** Summary of the PWA results. The first errors are statistical and the second ones are systematic.

| Resonance | Mass(MeV/$c^2$) | Width(MeV/$c^2$) | $\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$ | Significance |
|---|---|---|---|---|
| $f_0(1500)$ | $1468^{+14+23}_{-15-74}$ | $136^{+41+28}_{-26-100}$ | $(1.65^{+0.26+0.51}_{-0.31-1.40})\times10^{-5}$ | $8.2\ \sigma$ |
| $f_0(1710)$ | $1759\pm6^{+14}_{-25}$ | $172\pm10^{+32}_{-16}$ | $(2.35^{+0.13+1.24}_{-0.11-0.74})\times10^{-4}$ | $25.0\ \sigma$ |
| $f_0(2100)$ | $2081\pm13^{+24}_{-36}$ | $273^{+27+70}_{-24-23}$ | $(1.13^{+0.09+0.64}_{-0.10-0.28})\times10^{-4}$ | $13.9\ \sigma$ |
| $f_2'(1525)$ | $1513\pm5^{+4}_{-10}$ | $75^{+12+16}_{-10-8}$ | $(3.42^{+0.43+1.37}_{-0.51-1.30})\times10^{-5}$ | $11.0\ \sigma$ |
| $f_2(1810)$ | $1822^{+29+66}_{-24-57}$ | $229^{+52+88}_{-42-155}$ | $(5.40^{+0.60+3.42}_{-0.67-2.35})\times10^{-5}$ | $6.4\ \sigma$ |
| $f_2(2340)$ | $2362^{+31+140}_{-30-63}$ | $334^{+62+165}_{-54-100}$ | $(5.60^{+0.62+2.37}_{-0.65-2.07})\times10^{-5}$ | $7.6\ \sigma$ |

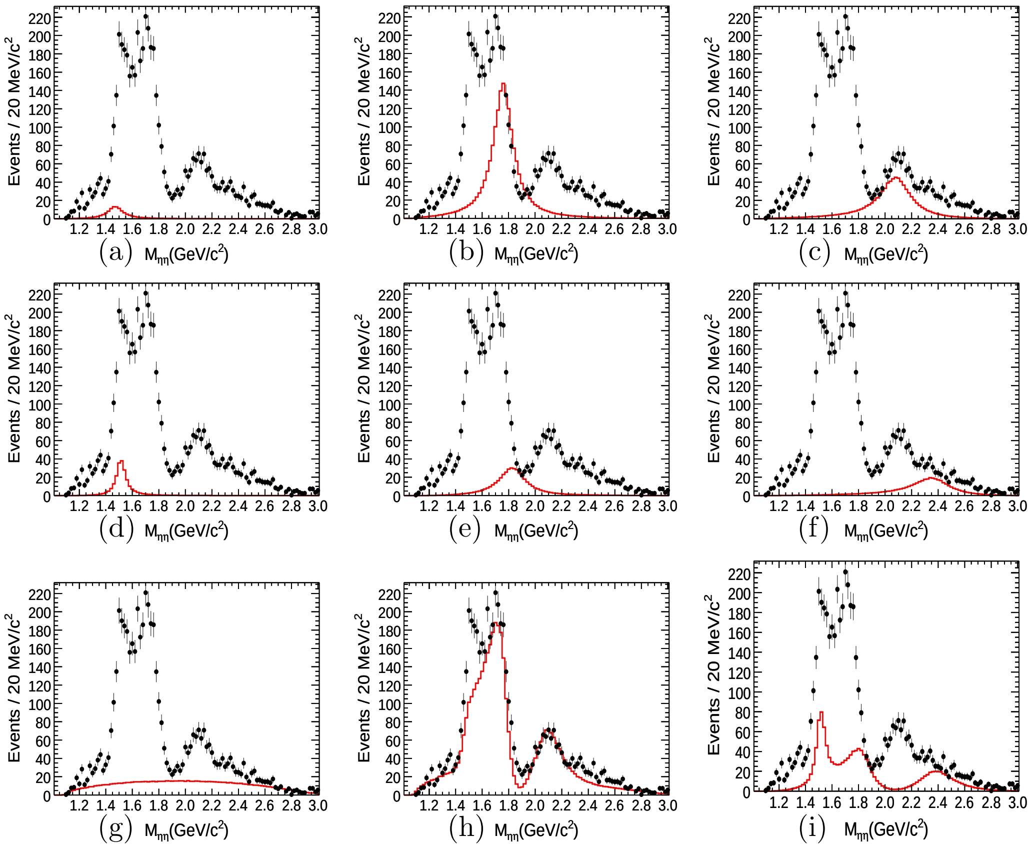


**Figure 1.** Contribution of the components. (a) $f_0(1500)$, (b) $f_0(1710)$, (c) $f_0(2100)$, (d) $f_2^{'}(1525)$, (e) $f_2(1810)$, (f) $f_2(2340)$, (g) $0^{++}$ phase space, (h) total $0^{++}$ component, and (i) total $2^{++}$ component. The dots with error bars are data with background subtracted, and the solid histograms are the projection of the PWA.

## 3. Observation of $\eta' \to \pi^+\pi^-\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\pi^0\pi^0$

This analysis [37] provides clean $\eta'$ data via $J/\psi$ radiative decay. The $\pi^+\pi^-\pi^+\pi^-$ invariant mass spectrum is shown in Fig. 2(a), where an $\eta'$ peak is clearly observed in the inset plot. The projections of the fit to $M_{\pi^+\pi^-\pi^{+(0)}\pi^{-(0)}}$ in the $\eta'$ mass region are shown in Figs. 2(b) and (c), where the shape of the sum of signal and background shapes agree well with data. $199 \pm 16$ $\eta' \to \pi^+\pi^-\pi^+\pi^-$ events was observed with a statistical significance of $18\sigma$ and $84 \pm 16$ $\eta' \to \pi^+\pi^-\pi^0\pi^0$ events with a statistical significance of $5\sigma$ respectively. The $M_{\pi^+\pi^-}$ spectrum of data carrying key information of $\eta'$ decay mechanism is extracted from fitting the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum and subtracting background. The MC spectrum employs two models, a phase space model and a combined model of ChPT and VMD implemented using decay amplitudes in Ref. [20]. To make comparison, the MC $M_{\pi^+\pi^-}$ spectrum is divided into 38 bins in the region of [0.28, 0.66] GeV/$c^2$ for decay of $\eta' \to \pi^+\pi^-\pi^+\pi^-$, as shown in Fig. 2 (d) (four entries per event), where the errors are statistical only. Clearly, the combined model agrees with data better than the phase space model. Branching fractions of $\mathcal{B}(J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\pi^+\pi^-)$ and $\mathcal{B}(J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\pi^0\pi^0)$ are determined to be $(4.40 \pm 0.35 \pm 0.30) \times 10^{-7}$ and $(9.38 \pm 1.79 \pm 0.89) \times 10^{-7}$ respectively.

## 4. Observation of two new $N^*$ resonances in $\psi(3686) \to p\bar{p}\pi^0$

This analysis[31] takes advantage of a data set with larger statistics than that at CLEOc shows more than one $N^*$ state below 1700 MeV/$c^2$, which are easily seen in the $p\pi^0$ and $\bar{p}\pi^0$ mass

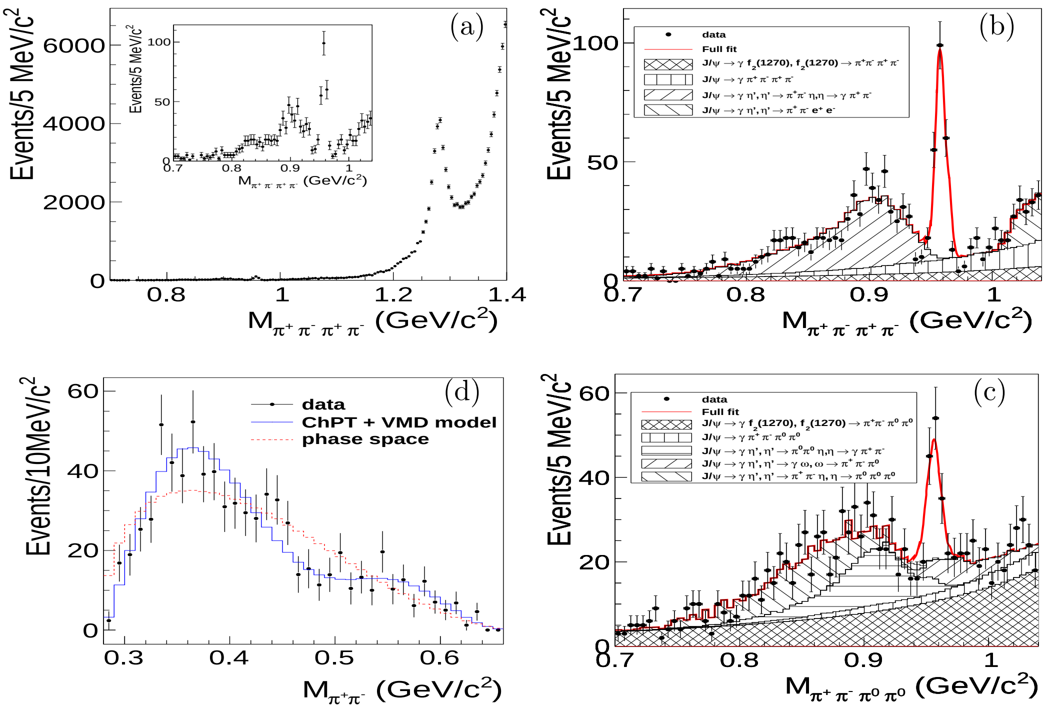


**Figure 2.** (a) The invariant mass distributions of $\pi^+\pi^-\pi^+\pi^-$. Results of the fits to (b) $M_{\pi^+\pi^-\pi^+\pi^-}$ and (c) $M_{\pi^+\pi^-\pi^0\pi^0}$, where the background contributions are displayed as the hatched histograms. (d) The comparison of $M_{\pi^+\pi^-}$ (four entries per event) between data and two different models, where the dots with error bars are for the background-subtracted data, the solid line is for the ChPT and VMD model, and the dashed line is for the phase space.

spectra, and the threshold enhancement in the $p\bar{p}$ mass spectrum. To better understand the structure of multi-resonances and their interference, a partial wave analysis is performed and components' contributions are shown in Fig. 3. Plot (a) shows the contributions of $N(1440)$, $N(1520)$, $N(1535)$ and $N(1650)$ with clear peaks, the tails at the high mass region come from the interference effects. Plot (b) shows the contributions of $N(940)$, $N(1720)$, $N(2300)$ and $N(2570)$. Two new $N^*$ resonances, $N(2300)$ and $N(2570)$ are observed with number of events $948 \pm 68$ and $795 \pm 45$ respectively. No clear evidence for $N(1885)$ or $N(2065)$ were found. More investigations such as $J/\psi \to \eta p\bar{p}$[33], $J/\psi \to \lambda\Sigma^0$[34], $\psi' \to \bar{p}K\Sigma^0$[35], $\chi_{c0} \to p\bar{n}\pi^-$[36] also explored new baryon states.

## 5. Summary

The PWA results of $J/\psi \to \gamma\eta\eta$ as summarized in Table 1 combining with branching fractions of $J/\psi \to \gamma f_0(1710) \to \gamma XX$, were employed to compare the recent lattice QCD prediction of $J/\psi \to \gamma G(0^{++})$ . A series of recently observed baryon states aim to improve further understanding of the quark model. The analyses of $\eta' \to \pi^+\pi^-\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\pi^0\pi^0$ agree with the combined model of chiral perturbation theory and vector-meson dominance approach.

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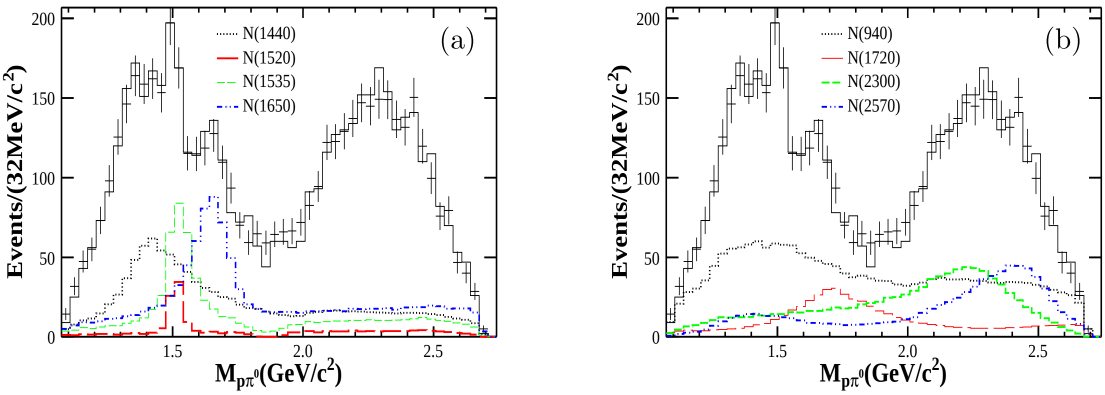


**Figure 3.** The contribution of each intermediate resonance in the $p\pi^0$ mass spectra. The interferences with other resonances are included.


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