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Observation of isoscalar 1^{-+} spin-exotic state $\eta_1(1855)$

RUNQIU MA on behalf of the BESIII COLLABORATION
Institute of High Energy Physics - Beijing, People's Republic of China

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Summary. — Using a sample of $(10.09 \pm 0.04)\times 10^9$ J/ψ events collected with the BESIII detector operating at the BEPCII storage ring, a partial wave analysis of the decay $J/\psi \to \gamma\eta\eta'$ is performed. The first observation of an isoscalar state with exotic quantum numbers $J^{PC} = 1^{-+}$, denoted as $\eta_1(1855)$, is reported in the process $J/\psi \to \gamma\eta_1(1855)$ with $\eta_1(1855) \to \eta\eta'$. Its mass and width are measured to be $(1855 \pm 9^{+6}_{-1})$ MeV/c^2 and $(188 \pm 18^{+3}_{-8})$ MeV, respectively, where the first uncertainties are statistical and the second are systematic, and its statistical significance is estimated to be larger than 19σ.

1. – Introduction

The quark model describes a conventional meson as a bound state of a quark and an antiquark. However, due to the non-Abelian nature of QCD, bound states with gluonic degrees of freedom, such as glueballs and hybrids, are also expected. The clear identification of these QCD exotics would validate and advance our quantitative understanding of QCD. Radiative decays of the J/ψ meson provide a gluon-rich environment and are therefore regarded as one of the most promising hunting grounds for gluonic excitations [1-4].

Hybrid mesons are $q\bar{q}$ states with explicit excitations of the gluon field. They were first proposed several decades ago [5-9], and have been the source of more recent lattice QCD (LQCD) [10-13] and phenomenological QCD studies [14-17]. Models and LQCD predict that the exotic $J^{PC} = 1^{-+}$ nonet of hybrid mesons is the lightest, with a mass around 1.7–2.1 GeV/c^2 [10, 13, 18]. The predicted decay widths are model dependent; most hybrids are expected to be rather broad, but some can be as narrow as 100 MeV [19]. There are currently three 1^{-+} candidates: the $\pi_1(1400)$, $\pi_1(1600)$, and $\pi_1(2015)$ [20-23], which are all isovector states. Finding an isoscalar 1^{-+} hybrid state is critical for establishing the hybrid multiplet. Decaying to $\eta\eta'$ in a P wave is expected for an isoscalar 1^{-+} hybrid state [24-26].

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

In this work [27, 28], a partial wave analysis (PWA) of the process $J/\psi \to \gamma\eta\eta'$ is performed based on $(10.09 \pm 0.04) \times 10^9$ J/ψ events accumulated with the BESIII detector [29] operating at the BEPCII storage ring. After event selection, for $J/\psi \to \gamma\eta\eta'$, $\eta' \to \eta\pi^+\pi^-$, the selected sample contains a total of 4788 candidate events including 391$\pm$9 background events, while for $J/\psi \to \gamma\eta\eta'$, $\eta' \to \gamma\pi^+\pi^-$, there are 10544 total events including 1336$\pm$21 background events. The four-momenta of the reconstructed γ, η, and η' are used to perform the PWA fit. To account for background, the background contribution to the likelihood function is estimated using η' sideband events and is subtracted from the total log-likelihood value [30]. Quasi-two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor amplitudes described in ref. [31]. A detailed description of the PWA can be found in ref. [28].

To describe the $\eta\eta'$ spectrum, all kinematically allowed resonances with $J^{PC} = 0^{++}$, 2^{++}, and 4^{++} listed in the PDG [32], ref. [33], and ref. [34] are considered. Similarly, to describe the $\gamma\eta^{(\prime)}$ spectrum, all resonances listed in the PDG with $J^{PC} = 1^{+-}$ and 1^{-} are considered. The 1^{-+} resonance is also considered in $\eta\eta'$ spectrum, due to the η and η' are not identical particles.

The resulting baseline set of amplitudes contains a significant contribution from an isoscalar state with exotic quantum numbers $J^{PC} = 1^{-+}$, denoted as $\eta_1(1855)$. After considering the systematic uncertainty, its statistical significance is larger than 19σ, and its mass and width are $(188 \pm 18^{+3}_{-8})$ MeV and $(188 \pm 18^{+3}_{-8})$ MeV, respectively. The baseline set of amplitudes also includes four 0^{++} resonances [$f_0(1500)$, $f_0(1810)$, $f_0(2020)$, $f_0(2330)$], two 2^{++} resonances [$f_2(1565)$, $f_2(2010)$], a non-resonant contribution modeled by a 0^{++} $\eta\eta'$ system uniformly distributed in phase space (PHSP), and two 1^{+-} resonances [$h_1(1415)$, $h_1(1595)$] in the $\gamma\eta$ system. In addition, a 4^{++} resonance $f_4(2050)$ with statistical significance 4.6σ is included. No significant contributions from additional resonances with conventional quantum numbers are found. The most significant additional contribution (4.4σ) comes from an exotic 1^{-+} component around 2.2 GeV. Figure 1 shows the invariant mass distributions of $M(\eta\eta')$, $M(\gamma\eta)$, $M(\gamma\eta')$ and the $\cos\theta_\eta$ distribution for the data (with background subtracted) and the PWA fit projections.

3. – Further checks on the $\eta_1(1855)$

Various checks are performed to validate the existence of the $\eta_1(1855)$. The fits are carried out by assigning all other possible J^{PC} ($J \leq 4$) to the $\eta_1(1855)$, and the log-likelihoods are worse by at least 235 units ($> 30\sigma$). To probe the significance of the BW phase motion, the BW parametrization of the $\eta_1(1855)$ in the baseline PWA is replaced with an amplitude whose magnitude matches that of a BW function but with constant phase (independent of s). This alternative fit has a log-likelihood 43 units (9.2σ) worse than the baseline fit.

To visualize the contribution from spin-0 (S), spin-1 (P) and spin-2 (D) waves, angular moments as a function of $M(\eta\eta')$ can be calculated for data (with background subtracted) and the PWA model. For events within a given region of $M(\eta\eta')$, the $\cos\theta_\eta$ distribution can be expressed as an expansion in terms of Legendre polynomials. The coefficients, which are called the unnormalized moments of the expansion, characterize the spin of the contributing $\eta\eta'$ resonances. The detailed description about angular moment $\langle Y_l^0 \rangle$ is shown in refs. [27, 28]. Figure 2 shows the moments computed for the data and the PWA

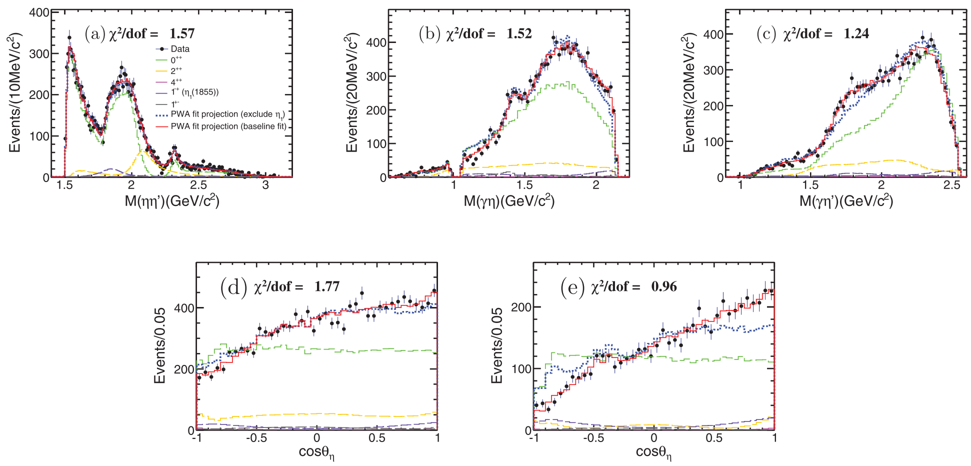

Fig. 1. – Background-subtracted data (black points) and the PWA fit projections (lines) for (a)–(c) the invariant mass distributions of (a) $\eta\eta'$, (b) $\gamma\eta$, and (c) $\gamma\eta'$, and (d), (e) the distribution of $\cos\theta_\eta$, where θ_η is the angle of the η momentum in the $\eta\eta'$ (Jocob and Wick) helicity frame for (d) all $\eta\eta'$ masses and (e) $\eta\eta'$ masses between 1.7 and 2.0 GeV/c^2.

model, where good data and PWA consistency can be seen. For $\langle Y_1^0\rangle$, the moments are related to the S, P and D waves by [35]

$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})), \quad (1)$$

where ϕ_P and ϕ_D are the phases of the P wave and D wave relative to the S wave. It is notable that each term in $\langle Y_1^0\rangle$ is related to the P wave. In the $\eta\eta'$ system, only η_1 can

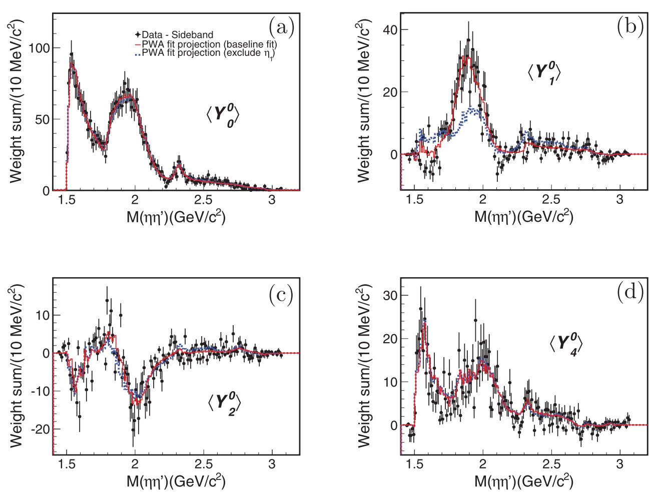

Fig. 2. – The distributions of the unnormalized moments $\langle Y_L^0\rangle$ (L = 0, 1, 2, and 4) for $J/\psi \to \gamma\eta\eta'$ as functions of the $\eta\eta'$ mass.

provide the P wave. The evident structure in $\langle Y_1^0 \rangle$ (fig. 2(b)) suggests the existence of $\eta_1(1855)$.

4. – Discussion of the $f_0(1500)$ and $f_0(1710)$

Assuming the glueball branching ratio $\mathcal{B}(G \to KK)/\mathcal{B}(G \to \pi\pi)$ is within the range of those measured for the $f_0(1710)$ in the PDG [32], ref. [36] predicts the ratio $\mathcal{B}(G \to \eta\eta')/\mathcal{B}(G \to \pi\pi)$ to be less than 0.04. In this work, the decay $J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta'$ is observed ($> 30\sigma$), while $J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta'$ is found to be insignificant. The ratio $\mathcal{B}(f_0(1500) \to \eta\eta')/\mathcal{B}(f_0(1500) \to \pi\pi)$ is measured to be $(1.66^{+0.42}_{-0.40}) \times 10^{-1}$. For the first time, the upper limit on the ratio of $\mathcal{B}(f_0(1710) \to \eta\eta')/\mathcal{B}(f_0(1710) \to \pi\pi)$ at 90% confidence level is determined to be 2.87×10^{-3}. The suppressed decay rate of the $f_0(1710)$ into $\eta\eta'$ lends further support to the hypothesis that the $f_0(1710)$ has a large overlap with the ground state scalar glueball [36], and the $f_0(1710)/f_0(2020)$ might be interpreted as flavor singlet [37].

5. – Conclusion

In summary, a PWA of $J/\psi \to \gamma\eta\eta'$ has been performed based on $(10.09\pm0.04)\times10^9$ J/ψ events collected with the BESIII detector. An isoscalar state with exotic quantum numbers $J^{PC} = 1^{-+}$, denoted as $\eta_1(1855)$, has been observed for the first time. Its mass and width are measured to be $(1855\pm9^{+6}_{-1})$ MeV/c^2 and $(188\pm18^{+3}_{-8})$ MeV, which are consistent with LQCD calculations for the 1^{-+} hybrid [13]. The first uncertainties are statistical and the second are systematic. The statistical significance of the resonance hypothesis is estimated to be larger than 19σ. The product branching fraction $\mathcal{B}(J/\psi \to \gamma\eta_1(1855))\mathcal{B}(\eta_1(1855) \to \eta\eta')$ is measured to be $(2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$. The mass and width of the $\eta_1(1855)$ are consistent with LQCD calculations for the 1^{-+} hybrids [13]. The observation of $\eta_1(1855)$ provides crucial information for the establishment of 1^{-+} exotic nonet. In addition, the $\eta_1(1855)$ also inspired many interpretations, such as hybrid [38-41], $K_1\bar{K}$ molecule state [42-44] and tetraquark [45]. Further study with more production mechanisms and decay modes will help to identify the nature of $\eta_1(1855)$.

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