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Discovery of a glueball-like particle X(2370) at BESIII

Beijiang Liu[a,*] **on behalf of the BESIII collaboration**

[a] *Institute of High Energy Physics, Beijing 100049, People's Republic of China*

E-mail: liubj@ihep.ac.cn

Radiative decays of the J/ψ provide a gluon-rich environment and are therefore regarded as one of the most promising hunting grounds for glueballs. Using the world's largest samples of J/ψ events produced in e^+e^- annihilation, BESIII performed the first measurements of the quantum numbers of the $X(2370)$. The measured mass and spin parity of the $X(2370)$ are consistent with the predictions of the lightest pseudoscalar glueball.

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*Speaker

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1. Introduction

Glueballs, quarkless color-singlet states, repesent the most direct prediction of Quantum Chromodynamics (QCD) as a consequence of the gluon self-interactions. The study of glueballs is pivotal for gaining insights into the gluon degree of freedom at low energy scales, which is crucial for understanding of non-perturbative QCD. Theoretical predictions from Lattice QCD (LQCD) and QCD-inspired models are mostly consistent. The lightest glueballs are expected to have quantum numbers $J^PC = 0^{++}, 2^{++}, 0^{-+}$, same as ordinary $q\bar{q}$ states, and they are expected to lie in the same mass region as conventional mesons [1–3]. This makes the identification of glueballs very challenging, both theoretically and experimentally. Glueballs should be supernumerary states with respect to $q\bar{q}$ multiplets, assuming a mixing between glueballs and nearby $q\bar{q}$ states. Glueballs are expected to be copiously produced in the glue-rich processes [4], such as radiative decays of the J/ψ, double-Pomeron exchange in pp collisions, and $p\bar{p}$ annihilations. The BESIII experiment collected 10 billion J/ψ events, providing an ideal laboratory for studying glueballs. While there are no rigorous predictions regarding their decay properties, glueballs, being flavor blind due to the nature of gluons, should exhibit no dominant decay mode and should display $SU(3)_{flavor}$ symmetry. This is analogous to the OZI-suppressed decays of charmonium, which also proceed via gluons [5, 6].

In the scalar sector, experimental data unambiguously indicate an overpopulation of states. However, determining the internal configuration of these states is even more challenging. Results from BESIII are instrumental in resolving ambiguities regarding scalar states. We have found that the measured branching fraction of $J/\psi \to \gamma f_0(1710))$ is one order of magnitude higher than that of the $f_0(1500)$ in final states of $\eta\eta$, $\pi^0\pi^0$ and $K^0_S K^0_S$ [7–9], and it is compitable with the LQCD prediction [10]. This suggests that the $f_0(1710)$ is likely to have a significant scalar glueball component. Recently, coupled channel analyeses with BESIII data identified a substantial glue contribution in the mass region around 1.7 GeV [13, 14]. Furthermore, from the decay property, the suppression of the $f_0(1710) \to \eta\eta'$ supports that it has a large overlap with a glueball [11].

The tensor sector is extremely complex, with a large number of resonances making their assignment difficult. We have observed that the $f_2(2340)$ is strongly produced in several channels of J/ψ radiative decays [7, 9, 12, 15]. Comparisons with LQCD predictions for the production rate of the tensor glueball in J/ψ radiative decays suggest that further study of additional decay modes of the $f_2(2340)$ is warranted. It should be noted that three tensors in $\pi - p$ reactions [16] are all seen in $J/\psi \to \gamma\phi\phi$, with a strong production of the $f_2(2340)$.

In the pseudoscalar sector, only the η, η', and their radial excitations are expected from the quark model. This provides a promising window for searching for new pseudoscalar states beyond the quark model. LQCD predicts the mass of the pseudoscalar glueball to be in the range of 2.3-2.6 GeV. In the history, the first glueball candidate was the $\iota(1440)$, observed in J/ψ radiative decays [17, 18]. The $\iota(1440)$ is now supposed to split into two states, $\eta(1405)$ and $\eta(1475)$ [19], with the lower-mass meson still considered a potential glueball candidate despite its mass being significantly less than LQCD predictions [1–3]. There is limited experimental information available above 2 GeV, where the pseudoscalar glueball is expected. For production properties, unlike the scalar and tensor sectors, the predicted branching fraction of the pseudoscalar glueball in J/ψ radiative decays is on par with that of pseudoscalar $q\bar{q}$ states. Regarding decay properties, although there is no model-independent prediction yet, the OZI-suppressed decays of η_c can offer guidance. It is a promising area to search for the pseudoscalar glueball in final states such as $\eta'\pi\pi$, $\eta' K\bar{K}$, $K\bar{K}\pi$, $K\bar{K}\eta$, and $\eta\pi\pi$, analogous to the decay pattern of η_c [19]. The decay pattern of η_c exhibits a clear feature of OZI-suppressed decay via gluons, i.e., there is no dominant decay mode, and the partial widths appear flavor symmetric.

2. Observaton of X(2370) and determination of its J^{PC} quantum numbers

A $\pi^+\pi^-\eta'$ resonance, the $X(2370)$, was observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ with a statistical significance greater than 6.4σ in the BESIII experiment [20]. Subsequently, the $X(2370)$ was seen in $J/\psi \to \gamma K^+K^-\eta$'[21]. And it was further observed in a combined measurement of $J/\psi \to \gamma K^+K^-\eta'$ and $J/\psi \to \gamma K^0_S K^0_S \eta'$ with a statistical significance of 8.3σ by BESIII [22]. Searches in other decay channels, such as $J/\psi \to \gamma\eta'\eta\eta$ [23] and $J/\psi \to \gamma\gamma\phi$ [24], have set upper limits consistent with predictions for a low-lying pseudoscalar glueball.

Utilizing $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a partial wave analysis (PWA) of the decay $J/\psi \to \gamma K^0_S K^0_S \eta'$ is performed to investigate the properties of the $X(2370)$ [25]. To mitigate complexities arising from additional intermediate processes, only events with $M_{K^0_S K^0_S} < 1.1$ GeV$/c^2$ are used. The mass and width of the $X(2370)$ are measured to be $2395 \pm 11(\text{stat})^{+26}_{-94}(\text{syst})$ MeV$/c^2$ and $188^{+18}_{-17}(\text{stat})^{+124}_{-33}(\text{syst})$ MeV, respectively. The product branching fraction is given by $\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to f_0(980)\eta'] \times \mathcal{B}[f_0(980) \to K^0_S K^0_S] = \left(1.31 \pm 0.22(\text{stat})^{+2.85}_{-0.84}(\text{syst})\right) \times 10^{-5}$. The statistical significance of the $X(2370)$ is greater than 11.7σ and its spin-parity is determined to be 0^{-+}. Figure 1 illustrates the comparison of mass and angular distributions between data and PWA fit projections, including the individual contributions from each component.

3. New decay modes of X(2370)

A preliminary study of $J/\psi \to \gamma K^0_S K^0_S \pi^0$ has been performed. Clear signals of $X(2370)$ and η_c are observed in the invariant mass spectrum of $K^0_S K^0_S \pi^0$, as shown in Figure 2(a). Similar observations were made in the preliminary study of $J/\psi \to \gamma\pi^0\pi^0\eta$, as shown in Figure 2(b). It is noteworthy that the $\eta(2320) \to \eta\eta\eta$ and $\eta\pi\pi$ [26] could potentially be the same state as the $X(2370)$ observed at BESIII. The presence of $X(2370)$ and η_c in the mass spectrum of $a^0_0(980)\pi^0$, with a requirement of $a^0_0(980)$ in the $\eta\pi^0$ system, is also evident in Figure 2(c). One-dimesional fits are performed to the invariant mass spectra of $K^0_S K^0_S \pi^0$, $\pi^0\pi^0\eta$, and $a^0_0(980)\pi^0$. The signal of $X(2370)$ is modeled using an acceptance-weighted Briet-Weigner function with a phase-space correction, while the smooth background is described by a Chebyshev polynomial. The corresponding fit results are shown in Figures 2(d)-(f). The significance of the $X(2370)$ signal exceeds 5 σ in all three final states, as determined by the change in log-likelihood values and degrees of freedom in fits with and without the signal hypotheses.

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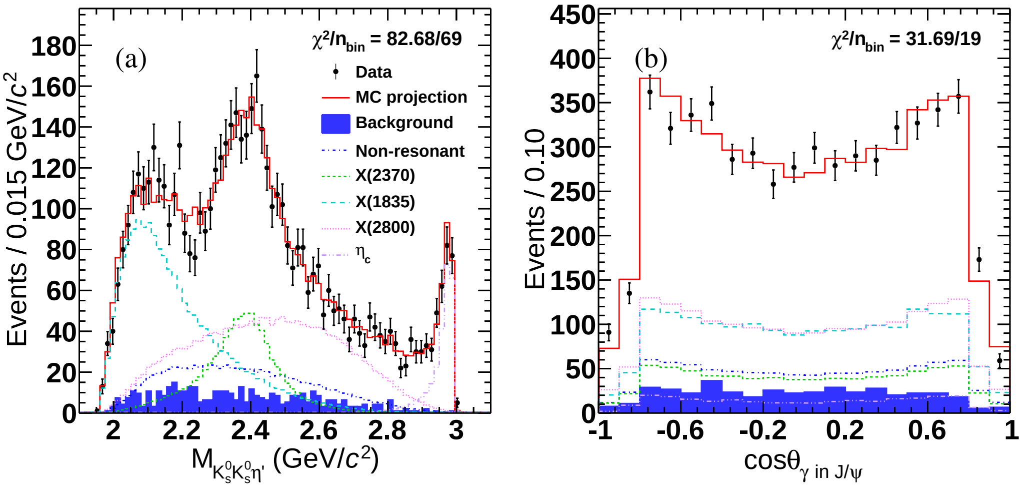

Figure 1: Comparisons between data (with two η' decay modes combined) and PWA fit projections: (a) is the invariant mass distribution of $K_S^0K_S^0\eta'$, and (b) is the angular distribution of $\cos\theta$, where θ is the polar angle of γ in the J/ψ rest system. The dots with error bars are data. The solid red histograms are the PWA total projections. The shaded histograms are the non-η' backgrounds described by the η' sideband. The dash-dotted blue, short dashed green, long dashed cyan, dotted magenta and dash-dot-dotted violet show the contributions of the non-resonant contribution, $X(2370)$, $X(1835)$, $X(2800)$ and η_c, respectively.

4. Summary

The spin-parity of the $X(2370)$ is determined to be 0^{-+} for the first time. The measured mass of $X(2370)$ and its production rate in the J/ψ radiative decays are in a good agreement with the LQCD predictions for the lightest pseudoscalar glueball, respectively. The observed decay modes of the $X(2370)$, including $\pi^+\pi^-\eta'$, $K\bar{K}\eta'$, $K_S^0K_S^0\pi^0$, $\pi^0\pi^0\eta$, and $a_0^0(980)\pi^0$, are analogous to those of the η_c meson. Further experimental and theoretical efforts are crucial for understanding of glueballs.

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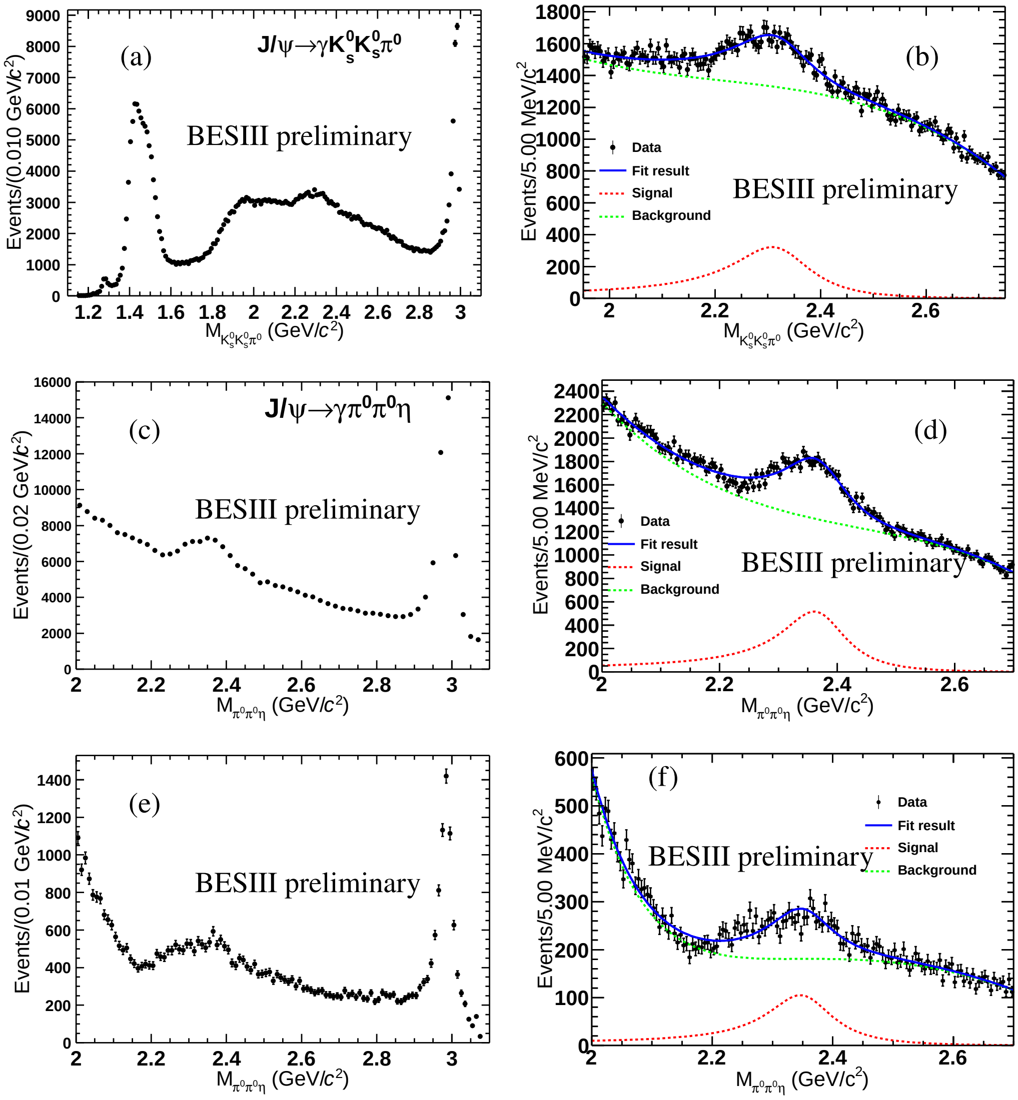

Figure 2: The invariant mass distributions and the one-dimensional fit results of (a)(b) $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$, (c)(d) $J/\psi \to \gamma\pi^0\pi^0\eta$ and (e)(f) $J/\psi \to \gamma a_0^0(980)\pi^0 \to \gamma\pi^0\pi^0\eta$.

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