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Measurement of the relative phase between strong and EM decays of charmonium

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Yuhan Fan[a,*] **and Yadi Wang**[a,*]

[a] *North China Electric Power University,*
Beinong Rd 2, Beijing, China

E-mail: `fanyuhanjy@163.com`, `wangyadi@ncepu.edu.cn`

A brief review of SU(3)-based analysis of the relative phase between the strong and electromagnetic (EM) amplitudes of charmonium is presented in this talk. Based on the scan method introduced at the BESIII experiment, the phase is directly measured from the line-shapes of the production cross sections of charmonium decaying to light hadrons, which are also presented in this talk. In the scan experiment, the interference between the continuum and the resonance is automatically subtracted. Mysteries about the phase, such as whether it is universal for all charmonium or even quarkonium, and what its exact value is, have not been solved yet. More experimental results about the phase are urgently needed to reach a physical and solid conclusion, and these results will further develop our understanding of the standard model.

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1. Introduction

The charmonium dominates a important position in the development of Quantum Chromodynamics (QCD) because they are three times heavier than the $\Phi(s\bar{s})$, where non-perturbative QCD (non-pQCD) is expected to dominate the OZI suppressed decays and, on the other hand, it is three times lighter than the $\Upsilon(b\bar{s})$, where perturbative QCD (pQCD) plays the main role [1]. As the two lowest lying state 1^{--}, J/ψ and $\psi(2S)$ decaying to hadrons are suppressed by the so-called OZI rule, and proceed through strong interaction via three gluons (A_g in Fig. 1 (a)) or electromagnetic interaction via one virtual photon (A_γ in Fig. 1 (b)).

The relative phase between the strong and the electromagnetic amplitudes of the charmounium decays is a basic parameter in understanding the decay dynamics. From pQCD, the coupling constants are all real in the EM and strong amplitudes. Thus, the relative phase between them should be 0° or 180°. Further, theorists [2–4] have argues that the relative phase is a manifestation of a kind of "universal incoherence". In order to arrive at a deeper understanding of the origin of large phase differences more experimental results are needed. In this talk, we review a series of experimental results on the phase difference.

2. SU(3) model dependent analysis results

The J/ψ and $\psi(2S)$ are two singlets under SU(3). Based on SU(3), the amplitudes of the various light final state hadron decays can be expressed in terms of an SU(3)-symmetric strong amplitude, a mass SU(3)-symmetry breaking amplitude, and one amplitudes involving electromagnetic. The contribution of these various amplitudes can be well defined with their transformation properties through standard SU(3) calculations. Considering the relevant decay amplitudes, the relative phase angle could be calculated with the experimental branching fractions.

The first experimental results for $J/\psi \to 1^-0^-$ decays coming from MARKIII [5] and DMII [6]. In a review of J/ψ decays [7], Köpke and Wermes confirmed the results of MARKIII and DMII with $\Phi = (72 \pm 17)^\circ$. Other theorists reanalyze the experimental results with their methods [1, 8, 9] and get the same conclusion. For the 0^-0^- pseudoscalar-pseudoscalar (PP) pairs, theorists have remarkably consistent results coming from Ref. [1, 7, 9, 10]. All of their results are consistent with $(90 \pm 10)^\circ$. For the baryon-antibaryon ($N\bar{N}$) pairs, the first analysis [11] is made based on the $J/\psi \to p\bar{p}$ and $n\bar{n}$ result from FENICE experiment, the phase turns out $\Phi = (89 \pm 15)^\circ$. In the same decay channel, BESIII [12] published the results with the first dataset collected. With isospin symmetry assumptions, the result of $\Phi = (88.7 \pm 8.1)^\circ$ is reported. Later on, BESIII ushers in more and more precise measurements of baryon pair decays which are reanalyzed in Ref. [13], and a phase of $\Phi = (90.8 \pm 1.6)^\circ$ or $\Phi = (-85.9 \pm 1.7)^\circ$ is obtained. Considering the contribution from strong-EM ($A_{gg\gamma}$) which the authors claim it cannot be neglected, Baldini [14] make their analysis again with the latest result of $J/\psi \to N\bar{N}$ decays, $\Phi = (73 \pm 8)^\circ$. For the other decay modes of J/ψ, i.e. 1^+0^- and 1^-1^-, results is relatively rare since the uncertainties of their branching ratios are large. Result from Suzuki [15] shows the phase favors a large angle, *i.e.*, 90°.

Come to the case of $\psi(2S)$ and $\psi(3770)$, the situation is not always the same as that of J/ψ. BESII [16] have investigated the analysis of $\psi(2S) \to K_S K_L$ and combining with $\psi(2S) \to \pi^+\pi^-$ and K^+K^- decays, the phase is determined as $\Phi = (82 \pm 29)^\circ$ or $\Phi = (+121 \pm 27)^\circ$. Later on,

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Metreveli [17] have finished the comprehensive study of $\psi(2S) \to PP$ based on CLEO-c data, and make a conclusion of $\Phi = (110.5^{+16.0}_{-9.5})^\circ$. Notice this interference effect, BABAR [18] claims that the branching ratio of $\psi(2S) \to K^+K^-$ probably have 15% deviation from its true value. For the $\psi(2S) \to VP$ mode, the experimental data are not enough to make a conclusion [19, 20], but the authors make a statement that the phase could be other value, i.e., 0°, and this could explain the so-called $\rho\pi$ puzzle. For $\psi(3770)$, based on the results of $\psi(3770) \to \rho\pi$ and $\psi(2S) - \psi(3S)$ mixing theory, Wang [20] gets a conclusion that the phase has a large possibility of -90°.

3. SU(3)-independent analysis with Scan experiment method

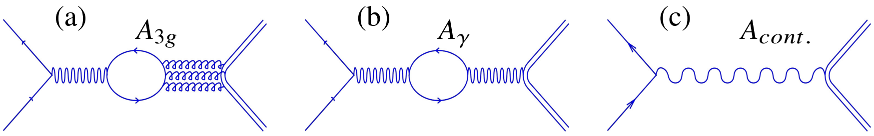

Figure 1: (a) $e^+e^- \to J/\psi \to$ hadrons *via* gluonic decay; (b) $e^+e^- \to J/\psi \to$ hadrons *via* one-photon decay; (c) non-resonant $e^+e^- \to$ hadrons *via* a vitrual photon.

Since all of the above analysis are involved theoretical assumptions relying on the SU(3) symmetry, the strong SU(3)-symmetry breaking, and so on, the measurements of these phases independent of SU(3) are urgent. Fortunately, it is possible to measure it from the scanning of the production cross section lineshape which involves the other diagram from continuum $A_{\text{cont.}}$, shown in Fig. 1 (c). The Born cross section could be written as:

$$\sigma^0(\sqrt{s}) = \beta^{2l+1}\left(\frac{\mathcal{F}}{s^{n/2}}\right)^2 \frac{4\pi\alpha^2}{3s} \frac{1}{|1-\Pi_0(s)|^2} \left|1 + (e^{i\Phi_{\text{cont.},\gamma}} + Ce^{i\Phi}) \times \frac{s}{M} \times \frac{3\Gamma^0_{ee}/\alpha}{s - M^2 + iM\Gamma}\right|^2, \quad (1)$$

where M and Γ are the mass and width of $\psi(2S)$, $\Gamma^0_{ee} = \Gamma_{ee}/|1-\Pi_0(s)|$ is the physical partial widths of $\psi(2S) \to e^+e^-$. The term $\frac{1}{|1-\Pi_0(s)|^2}$ is the vacuum polarization factor, β^{2l+1} is the phase-space factor, and $(\frac{\mathcal{F}}{s^{n/2}})^2$ is the form factor specialized for final hadrons. The phase $\Phi_{\text{cont.},\gamma}$ is relative phase between $A_{\text{cont.}}$ and A_γ, which is verified in $J/\psi \to \mu^+\mu^-$ in experiments [21, 22] as well as $J/\psi \to \mu^+\mu^-$ and $\eta\pi^+\pi^-$ described below. With the dataset recorded with the BESIII detector, which is described in detail in Ref. [23], we make the following analysis on the relative phase ϕ.

3.1 Analysis results for $J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$, $\mu^+\mu^-$ and $\eta\pi^+\pi^-$

Based on the dataset collected in 2012 at 16 different center of mass (CM) energies with a total integrated luminosity of about 100 pb^{-1}, analysis in $J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$, $\mu^+\mu^-$ and $\eta\pi^+\pi^-$ channels are made [24]. The lineshapes of the observed cross sections of these three channels are shown in Fig. 2, with the fitting curves. The initial-state-radiation (ISR) and beam energy spread are both considered in the fitting. From analysis of $\mu^+\mu^-$, the relative phase beween A_{cont} and A_γ, $\Phi_{\text{cont.},\gamma} = (3.0 \pm 10.0)^\circ$. From $\eta\pi^+\pi^-$, the phase $\Phi_{\text{cont.},\gamma} = (-2 \pm 36)^\circ$ or $(-22 \pm 36)^\circ$. Both results for $\Phi_{\text{cont.},\gamma}$ from these two channels are consistent with zero and theoretical prediction. From $\pi^+\pi^-\pi^+\pi^-\pi^0$, the phase between EM and strong amplitudes is measured as $\Phi = (84.9 \pm 3.6)^\circ$ with $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0) = (4.73 \pm 0.44)\%$ or $\Phi = (-84.7 \pm 3.1)^\circ$ with $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0) = (4.85 \pm 0.45)\%$.

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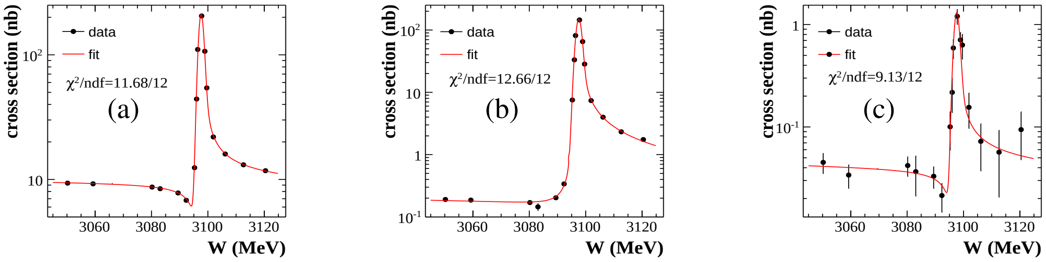

Figure 2: The lineshapes of e^+e^- annihilates to (a) $\mu^+\mu^-$, (b) $\pi^+\pi^-\pi^+\pi^-\pi^0$, and (c) $\eta\pi^+\pi^-$. The black points with error bars are data, and the solid lines show the fit results.

3.2 Analysis results for $J/\psi \to \phi\eta$

In this analyis, the data samples collected in 2012, 2015, 2018, and 2019 at 26 different CM energies with a total integrated luminosity of about 452 pb^{-1} are used [25]. The observe cross section lineshape is shown in Fig. 3 (a). Two separate solutions with positive and negative phases for Φ are found, as shown in Fig. 3 (b), while they are indistinguishable within the 1σ confidence interval. Thus, the relative phase Φ is reported as to be within the range of $[133.1°, 229.2°]$ within a 1σ confidence interval. This result may suggest an interference between the strong and EM amplitudes.

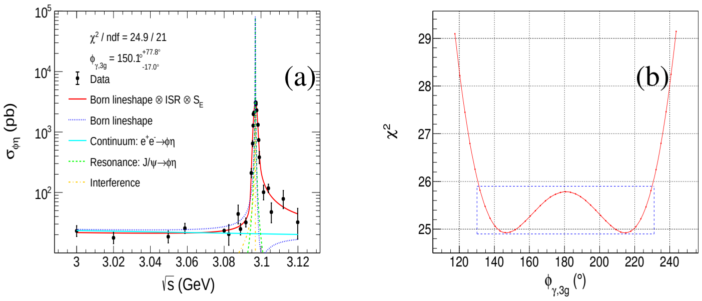

Figure 3: (a) The black points with error bars are data for the lineshape of $J/\psi \to \phi\eta$, and the solid lines show the fit results. (b) χ^2_2-scan over a range of Φ. The dashed line represents the interval which corresponds to a 1σ confidence interval.

3.3 Analysis results for $\psi(3770) \to p\bar{p}$

Using 2917 pb^{-1} of data collected at 3.773 GeV, 44.5 pb^{-1} of data collected at 3.65 GeV and data collected during a $\psi(3770)$ line-shape scan, the reaction $e^+e^- \to p\bar{p}$ has been studied [26]. The line-shape of the dressed cross section which is the sum of the Born cross section and the contribution of vacuum polarization is shown in Fig. 4 (a). The fitting formula used here has some difference from Eq. 1, and focuses on the interference between the continuum and the $\psi(3770)$

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resonance, as Eq. 2 shows.

$$\sigma^0(\sqrt{s}) = |A_{con} + A_\psi e^{i\Phi}|^2 = |\sqrt{\sigma_{con}}(\sqrt{s}) + \sqrt{\sigma_\psi}\frac{m_\psi \Gamma_\psi}{s - m_\psi^2 + i m_\psi \Gamma_\psi}|^2, \tag{2}$$

where m_ψ and Γ_ψ are the mass and width of $\psi(3770)$, σ_ψ is the resonant cross section, which is set as a free parameter, and Φ describes the phase angle between the continuum and resonant amplitudes. From fit, two solutions are found: $\Phi = (255.8^{+39.0}_{26.6} \pm 4.8)^\circ$ with $\sigma_{\psi(3770)\to p\bar{p}} < 0.166$ pb at 90% confidence level, and $\Phi = (266.9^{6.1}_{-6.3} \pm 0.9)^\circ$ with $\sigma_{\psi(3770)\to p\bar{p}} = 2.57^{+0.12}_{-0.13} \pm 0.12$ pb.

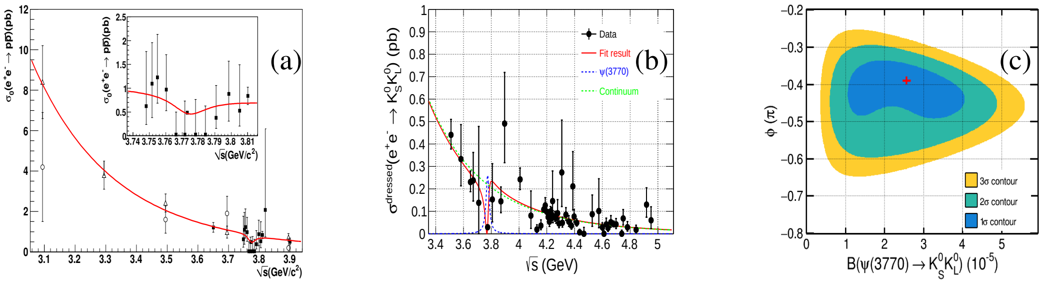

Figure 4: (a) Fit to the dressed cross section of $e^+e^- \to p\bar{p}$ around $\psi(3770)$. The red solid line shows the fit curve. The solid square points with error bars are from BESIII. The open circles and the open triangles are from the BABAR measurements. (b) Dressed cross sections of $e^+e^- \to K_S K_L$. Dots with error bars are data. Red solid, green dashed, and blue dashed lines are the fit results, the continuum production, and the $\psi(3770)$ production, respectively. (c) The likelihood contours in the $\mathcal{B}(\psi(3770) \to K_S K_L)$ and the relative phase Φ plane. The filled areas are up to 3σ likelihood contours. The red cross shows the local minimum.

3.4 Analysis results for $\psi(3770) \to K_S K_L$

Using the datasets at center-of-mass energies ranging from 3.51 to 4.95 GeV, corresponding to a total integrated luminosity of 26.5 fb^{-1}, the decay of $e^+e^- \to K_S K_L$ has been investigated. The dressed cross section around $\psi(3770)$ is measured, as shown in Fig. 4 (b). With a similar equation as Eq. 2, the line-shape is described with an incoherent interference $\Phi = (-0.39^{+0.05}_{-0.10})\pi$ and the branching ratio $\mathcal{B}(\psi(3770) \to K_S K_L) = (2.63^{+1.40}_{-1.59}) \times 10^{-5}$. A likelihood scan in the $\mathcal{B}(\psi(3770) \to K_S K_L)$ versus Φ plane is performed, shown as Fig. 4 (c). The significance of the $\psi(3770)$ resonance contribution is determined to be 10σ which is for the first time a discovery of the charmless decay of $\psi(3770)$. In this work, the ratio of neutral-to-charged kaon form factors upto a large momentum transfer is also determined, refer to Ref. [27].

4. Summary

A comprehensive review of the measurements in phase has been done in this paper. Up to now, the critical questions have not been answered. Is the phase universal for all charmounium decays, even for all decays related to strong and EM mechanisms? What is the exact value of the phase? To answer these questions, more experimental results either from model-dependent or model-independent are urgently needed. We have reasons to expect this could be solved in the BESIII, BELLE or LHCb experiments.

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