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

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Outline

Theory for the phase between strong and EM

SU(3) dependent experimental evidences

Scan method (SU(3) independent) and measurement

Summary
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Summary
Theory for the phase between strong and EM

(a) Strong $\rightarrow A_{3g}$

(b) Electromagnetic $\rightarrow A_\gamma$

(a) $e^+e^- \rightarrow R(qq) \rightarrow$ hadrons via strong mechanism;

(b) $e^+e^- \rightarrow R(qq) \rightarrow$ hadrons via EM mechanism;

pQCD regime: all are Real, phase between $A_{3g}$ and $A_\gamma$ should be $0^\circ$ or $180^\circ$

Theory for the phase between strong and EM

\[ A_g^H = \sum_h \langle h|3g\rangle\langle 3g|\psi \rangle \]

\[ A_\gamma^H = \sum_h \langle h|\gamma\rangle\langle \gamma|h \rangle \]

Clearly,

\[ A_g^H A_\gamma^H = \langle \psi|3g\rangle\langle 3g|\Sigma_h\langle h|\langle h|\rangle|\gamma \rangle = 0 \]

is equivalent to

\[ \langle 3g|\gamma \rangle = 0 \]

Since \[ \Sigma_h|h\rangle\langle h| = 1 \]

Universality independent of final states or intermediate resonances.

For exclusive channels common to \( J/\psi \) and \( \psi(2S) \), there cannot be significant differences in relative abundances if the three gluon intermediate state makes any physical sense.

J.-M. Gerard, J. Weyers, Phys. Lett. B 462, 324 (1999);

P. Wang, C.Z. Yuan, X.H. Mo, Phys. Rev. D 69, 057502 (2004);

M. Suzuki, Phys. Rev. D 58, 111504 (1998); etc.
Theory for the phase between strong and EM

SU(3) dependent experimental evidences

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Summary
Model dependent experimental evidences from $J/\psi$ decays

SU3 and SU3 Breaking in $1^0-[1,2,3,4]$, $0^0-[1,2,3]$, $1^1-[1]$, $1^+0-[5]$, $B\bar{B}[2,6,7]$ decays show the phase in $J/\psi$ decays between $A_g$ and $A_\gamma$ is $\Phi \sim 90^\circ$

- $PP(0^-0^-)(\pi^+\pi^-, K^+ K^-, K_S K_L)$: $\Phi = (90 \pm 10)^\circ$ \cite{2}
- $VP(1^-0^-)(\rho \pi, \omega \pi^0, \phi \pi^0, \rho \eta, \omega \eta, \phi \eta, \rho \eta^\prime, \omega \eta^\prime, \phi \eta^\prime, \bar{K}^* K)$
- $VP(1^+0^-)(K_1^+(1400)K^+, K_1^+(1270)K^+)$
- $VV(1^-1^-)(\rho^+ \rho^-, K^{*+} K^{*-}, K^0 \bar{K}^0)$
- $B\bar{B}(p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}, \Sigma^0 \bar{\Sigma}^0, \Sigma^+ \bar{\Sigma}^-, \Sigma^- \bar{\Sigma}^+, \Xi^0 \bar{\Xi}^0, \Xi^+ \bar{\Xi}^-, \Sigma^0\Lambda + \bar{\Sigma}^0\bar{\Lambda})$

Some are based on very old experimental results, but the conclusion keeps the same

\begin{table}[h]
<table>
<thead>
<tr>
<th>Process \ $J/\psi \rightarrow PV$</th>
<th>SOZI amplitude</th>
<th>DOZI correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^+ \pi^-, \rho^0 \pi^0, \rho^0 \pi^-$</td>
<td>$g + e$</td>
<td>$g(1 - s_\rho) + e$</td>
</tr>
<tr>
<td>$K^* K^-, K^* K'$</td>
<td>$g(1 - s_\rho^*) - 2e$</td>
<td>$\sqrt{2}g\sqrt{2}X_n + Y_n$</td>
</tr>
<tr>
<td>$\omega \eta$</td>
<td>$(g + e)X_n$</td>
<td>$\sqrt{2}g\sqrt{2}X_n + Y_n$</td>
</tr>
<tr>
<td>$\omega \eta^\prime$</td>
<td>$(g + e)X_n$</td>
<td>$\sqrt{2}g\sqrt{2}X_n + Y_n$</td>
</tr>
<tr>
<td>$\phi \eta$</td>
<td>$[g(1 - 2s_\rho) - 2e]Y_n$</td>
<td>$\sqrt{2}g\sqrt{2}X_n + Y_n$</td>
</tr>
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</tr>
<tr>
<td>$\rho \eta$</td>
<td>$3eX_n$</td>
<td>$3eX_n$</td>
</tr>
<tr>
<td>$\rho \eta^\prime$</td>
<td>$3eX_n$</td>
<td>$3eX_n$</td>
</tr>
<tr>
<td>$\omega \pi^0$</td>
<td>$3e$</td>
<td>$3e$</td>
</tr>
<tr>
<td>$\phi \pi^0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

An example $g - A_{3g}; e - A_\gamma$

$X_\eta, Y_\eta, s_\eta \text{ SU}(3)\text{ breaking items}$

\cite{1,2,3,4,5,6,7}
BESIII datasets

Low energies can be accessed via ISR technique

Data below open-charm threshold:
- 2.23-3.67 GeV: 14 points \( \sim 110 \text{ pb}^{-1} \)
- 2.00-3.08 GeV: 21 points \( \sim 550 \text{ pb}^{-1} \)

Data above open-charm threshold:
- 3.85-4.59 GeV: 104 points, \( \sim 800 \text{ pb}^{-1} \)
- \( J/\psi \): 10 \text{ B}
- \( \psi(2S) \): 2.7\times10^9
- \( \psi(3770) \): 2.9 \text{ fb}^{-1}
- \( \psi(4040) \): 0.5 \text{ fb}^{-1}
- \( \psi_{4S} \): 4.23+4.26:1.0 \text{ fb}^{-1}
- \( \psi_{3770} \): 4.36 \text{ fb}^{-1}
- \( \psi_{4040} \): 4.42 \text{ fb}^{-1}
- \( R \) scan data above open-charm threshold
- \( R \): \( \sim 3 \text{ fb}^{-1} \)
- \( R \): \( \sim 6.3 \text{ fb}^{-1} \) in total
Model dependent experimental evidences from $J/\psi$ decays

Study of $J/\psi \rightarrow p\bar{p}$ and $J/\psi \rightarrow n\bar{n}$

$\phi = \cos^{-1}[(\mathcal{B}(J/\psi \rightarrow p\bar{p}) - S^2 - E_p^2)/(2SE_p)]$
= $(88.7 \pm 8.1)^\circ$.

$Br(J/\psi \rightarrow p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$
$\alpha = 0.595 \pm 0.012 \pm 0.015$

$Br(J/\psi \rightarrow n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$
$\alpha = 0.50 \pm 0.04 \pm 0.21$

- $E_p(E_n)$ and $S$ are EM and strong amplitudes of $J/\psi \rightarrow p\bar{p}$ ($n\bar{n}$), $\phi$ is the phase angle between $E_p(E_n)$ and $S$.
- Assumption:
  - $E_n = -E_p$ and $S_p = S_n = S$
- The strong interaction is dominant.
- $\Phi = (-85.9 \pm 1.7)^\circ$ or $(+90.8 \pm 1.6)^\circ$ combined with other baryon decays from BES, MarkII, DMII, BESII, BESIII experiments. K. Zhu, X. H. Mo, C. Z. Yuan, Inter. J. Mod. Phys. A, 30, 1550148 (2015)
Model dependent experimental evidences from $J/\psi$ decays

- Consider the small contribution from $A_{gg\gamma}$
- Assume $A_{gg\gamma}$ has the same phase as $A_g$ to $A_\gamma$
- Perform SU(3) analysis based on experimental branching ratios of $J/\psi$ decaying to baryons

$$\Phi = (73 \pm 8)^\circ$$

Br result from SU(3) very close to PDG

<table>
<thead>
<tr>
<th>$B\bar{B}$</th>
<th>$\text{BR}^{\text{exp}}_{B\bar{B}} \times 10^3$</th>
<th>$\text{BR}_{B\bar{B}} \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma^0\bar{\Sigma}^0$</td>
<td>$1.164 \pm 0.004$</td>
<td>$1.160 \pm 0.041$</td>
</tr>
<tr>
<td>$\Lambda\bar{\Lambda}$</td>
<td>$1.943 \pm 0.003$</td>
<td>$1.940 \pm 0.055$</td>
</tr>
<tr>
<td>$\Lambda\bar{\Sigma}^0 + \text{c.c.}$</td>
<td>$0.0283 \pm 0.0023$</td>
<td>$0.0280 \pm 0.0024$</td>
</tr>
<tr>
<td>$p\bar{p}$</td>
<td>$2.121 \pm 0.029$</td>
<td>$2.10 \pm 0.16$</td>
</tr>
<tr>
<td>$n\bar{n}$</td>
<td>$2.09 \pm 0.16$</td>
<td>$2.10 \pm 0.12$</td>
</tr>
<tr>
<td>$\Sigma^+\bar{\Sigma}^-$</td>
<td>$1.50 \pm 0.24$</td>
<td>$1.110 \pm 0.086$</td>
</tr>
<tr>
<td>$\Sigma^-\bar{\Sigma}^+$</td>
<td>/</td>
<td>$0.857 \pm 0.051$</td>
</tr>
<tr>
<td>$\Xi^0\bar{\Xi}^0$</td>
<td>$1.17 \pm 0.04$</td>
<td>$1.180 \pm 0.072$</td>
</tr>
<tr>
<td>$\Xi^-\bar{\Xi}^+$</td>
<td>$0.97 \pm 0.08$</td>
<td>$0.979 \pm 0.065$</td>
</tr>
</tbody>
</table>
Model dependent experimental evidences from $\psi(2S)$ decays

From the analysis of BESIII data made by R. Baldini\textsuperscript{[1]}:

- $\psi(2S) \to VP (1^-0^-)$: $\Phi = (159 \pm 12)^\circ$
- $\psi(2S) \to K^*K$ only: $\Phi = (159 \pm 24)^\circ$
- $\psi(2S) \to PP (0^-0^-)$: $\Phi = (95 \pm 11)^\circ$

Analysis by Mahiko Suzuki\textsuperscript{[2]} with Babar data:

- $\psi(2S) \to 1^-0^-$: tends to have large phase,
- $\psi(2S) \to 1^+0^-$: $\Phi \sim 0^\circ$
- Difference could be caused by lower statistics of Babar data than that of BESIII.

PP$(0^-0^-)$ mode from BES result\textsuperscript{[3]}:

- $\psi(2S) \to K_SK_L, K^+K^-, \pi^+\pi^-$:
  $\Phi = (-82 \pm 29)^\circ$ or $(121 \pm 27)^\circ$

Analysis\textsuperscript{[4]} of $\psi(2S)$ decaying to baryon pairs from CLEO and BESII:

- baryon pairs:
  $\Phi = (-98 \pm 25)^\circ$ or $(+134 \pm 25)^\circ$

\textsuperscript{[1]} Rinaldo Baldini Ferroli, Orsay (France), 2014
Model dependent experimental evidences from $\psi(3770)$ decays

- From R. Baldini (Orsay (France), (2014)), $|\Phi| \sim 90^\circ$

<table>
<thead>
<tr>
<th>decay</th>
<th>continuum</th>
<th>$\Psi''(3770)$</th>
<th>sign</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho \pi$</td>
<td>$13.1 \pm 2.8$</td>
<td>$7.4 \pm 1.3$</td>
<td>-</td>
<td>CLEOc, PRD 73(2006)012002</td>
</tr>
<tr>
<td>$\phi \eta$</td>
<td>$2.1 \pm 1.6$</td>
<td>$4.5 \pm 0.7$</td>
<td>+</td>
<td>CLEOc, PRD 73(2006)012002</td>
</tr>
<tr>
<td>$\rho \rho$</td>
<td>$0.74 \pm 0.08$</td>
<td>$0.4 \pm 0.02$</td>
<td>-</td>
<td>BESIII Y.Liang, Nov (2012)</td>
</tr>
</tbody>
</table>

- From P. Wang (arxiv:hep/0410028v2 (2004)),
  - $\Phi$ holds $-90^\circ$ in OZI suppressed decays of $\psi(3770)$.
  - From the $\rho \pi$ cross section measurement at $\psi(3770)$ and 3.67 GeV, $\rho \pi$ production is suppressed possibly by interference.
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Summary
SU(3) independent--Scan method

\[ \sigma_{\text{born}} = |A_{3g}e^{i\Phi_{g,\text{cont.}}} + A_\gamma e^{i\Phi_{\gamma,\text{cont.}}} + A_{\text{cont.}}|^2 \]

If \( \Phi_{3g,\text{cont.}} = 0^\circ \),

\[ \sigma_{\text{born}} = |A_{3g}e^{i\Phi_{g,\text{EM}}} + A_\gamma + A_{\text{cont.}}|^2 \]

◆ The full interference between \( A_\gamma \) and \( A_{\text{cont}} \) has been observed at SLC (1975), BESII (1995) and KDER (2010). (\( \Phi_{\gamma,\text{cont.}} = 0^\circ \))
Model dependent experimental evidences from $\phi$ decays

The interference between $\phi$ and $\omega(\omega')$ was observed at SND.

- $e^+ e^- \rightarrow \phi \rightarrow \pi^+ \pi^- \pi^0$:
  - $A_\gamma$ is dominate

- $e^+ e^- \rightarrow \omega(\omega') \rightarrow \pi^+ \pi^- \pi^0$:
  - $A_{3g}$ is dominate

- $\Phi_{\phi - \omega(\omega')} \sim \Phi_{g,\gamma}$

- $\Phi_{\phi - \omega(\omega')} \sim 180^\circ [1]$

Scan method and measurement

• The born cross section:

\[ \sigma^0(W) = \left( \frac{A}{W^2} \right)^2 4\pi \alpha^2 \left| 1 + \frac{3W^2\sqrt{\Gamma_{e}\Gamma_{\mu\mu}} (1 + Ce^{i\Phi_{g,EM}})}{\alpha M(W^2 - M^2 + iMT)} \right|^2 \]

• The observed cross section:

\[ \sigma^{\text{theory}}(W) = \int_{W-nS_E}^{W+nS_E} GS(W - W'') dW'' \int_{0}^{x_f} dx F(x, s) \sigma^{0}(s(1-x)) \]

• Minimization method:

\[ \chi^2 = \sum_{i=1}^{16} \frac{\left[ \sigma_{i}^{\text{obs}} - f\sigma''(W_i) \right]^2}{(\Delta \sigma_{i}^{\text{obs}})^2 + \left[ \Delta W_i \cdot \frac{d\sigma''(W)}{dW} \right]^2} + \left( \frac{1-f}{\Delta f} \right)^2 \]

Scan method and measurement


\[ e^+ e^- \rightarrow J/\psi \rightarrow 2(\pi^+\pi^-)\pi^0 \]

- \(J/\psi\) scan data (16 data points) of 100 \(pb^{-1}\) collected in 2012 is used.
- Detection efficiency is simulated with MCGPJ generator for the ISR effect around \(J/\psi\) narrow peak.
- Intermediate resonances are considered in simulation without interference.

<table>
<thead>
<tr>
<th>(\Phi_{g,EM})</th>
<th>(B_{5\pi}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution I</td>
<td>(84.9 ± 3.6)°</td>
</tr>
<tr>
<td>Solution II</td>
<td>(−84.7 ± 3.1)°</td>
</tr>
</tbody>
</table>

The phase between \(A_{\gamma}\) and \(A_{3g}\) is found being consistent with 90°.
Scan method and measurement

\[ e^+ e^- \rightarrow J/\psi \rightarrow \mu^+ \mu^- , \eta \pi^+ \pi^- \]

\[ \Phi \] represents the interference between \( J/\psi \rightarrow \eta \rho \) and \( J/\psi \rightarrow \rho \omega \)

\[ \sigma^0(W) = \frac{4\pi \alpha^2}{W^2} \left| 1 + \frac{3W^2}{\alpha M(W^2 - M^2 + iM\Gamma)} e^{i\Phi_Y,\text{cont.}} \right|^2 \]

- \( \Phi_Y,\text{cont.} = (3.0 \pm 10.0) \)°
- \( S_E = (0.90 \pm 0.03) \) MeV

\[ \sigma^0(W) = \left( \frac{\mathcal{A}}{W^2} \right)^2 \frac{4\pi \alpha^2}{W^2} \left| 1 + \frac{3W^2}{\alpha M(W^2 - M^2 + iM\Gamma)} e^{i\Phi_{Y,\text{cont.}} + i\Phi} \right|^2 \]

- \( \Phi_{Y,\text{cont.}} = (-2 \pm 36) \)° or \(( -22 \pm 36) \)°
- \( Br(J/\psi \rightarrow \eta \pi^+ \pi^-) = (3.78 \pm 0.66) \times 10^{-4} \)
- \( Br_{PDG}(J/\psi \rightarrow \eta \pi^+ \pi^-) = (4.0 \pm 1.7) \times 10^{-4} \)

Once again, the phase between \( A_Y \) and \( A_{\text{cont.}} \) is confirmed to be ZERO.
Scan method and measurement

BESIII Collaboration, to be submitted

\( e^+e^- \rightarrow J/\psi \rightarrow \phi \eta \)

- Two solutions
- Indistinguishable within 1\(\sigma\) confidence
- \(\Phi_{3g,\gamma} \in [133.1^\circ, 229.2^\circ]\)

Interference between \(A_{3g}\) and \(A_\gamma\)?
Even the interference is between $A_{\text{con}}$ and $A_{\psi}$, the phase $\Phi_{3g,\gamma}$ is still close to $-90^\circ$ since $A_g$ is much larger than $A_{\gamma}$.
Scan method and measurement

BESIII Collaboration, Phys. Rev. Lett. 132, 131901 (2024)

\[ e^+ e^- \rightarrow \psi(3770) \rightarrow K_SK_L \]

\[ \mathcal{B} = (2.63^{+1.40}_{-1.59}) \times 10^{-5} \text{ and } \phi = (-0.39^{+0.05}_{-0.10})\pi \]

within 1\( \sigma \) likelihood contour.

• Significance of \( \psi(3770) \) resonance contribution determined to be 10\( \sigma \).

• First observe the charmless decay \( \psi(3770) \rightarrow K_SK_L \).

\[ \sigma^{\text{dressed}} = \left| B W \cdot e^{i\phi} + \frac{a}{(\sqrt{s})^n} \cdot \sqrt{\Phi(\sqrt{s})} \right|^2 \]

\[ B W = \sqrt{\frac{12\pi\Gamma_{ee}\Gamma_B}{s-M^2+iM\Gamma}} \frac{\Phi(s)}{\sqrt{\Phi(M)}} \Phi(s) = \frac{q^3}{s} \]
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Summary
The phase between strong and EM can be measured with SU(3) dependent method and scan method.

Critical problems about the phase is a mystery:
- Is the phase universal? Independent of initial or final state?
- What is the sign of the phase?

More experimental results are needed for a physical conclusion.

Direct scanned experimental result in $J/\psi$ and $\psi(3770)$ are shown, more results for $J/\psi$, $\psi(2S)$, $\psi(3770)$ will come.
Thanks for your attention!
Model dependent experimental evidences

Study of $J/\psi \rightarrow p\bar{p}$ and $J/\psi \rightarrow n\bar{n}$


- $Br(J/\psi \rightarrow p\bar{p}) = (2.112 \pm 0.004 \pm 0.031) \times 10^{-3}$
- $\alpha = 0.595 \pm 0.012 \pm 0.015$
- $Br(J/\psi \rightarrow n\bar{n}) = (2.07 \pm 0.01 \pm 0.17) \times 10^{-3}$
- $\alpha = 0.50 \pm 0.04 \pm 0.21$

- The $\alpha$ values are very close in two decay modes, which is expected if the strong interaction is dominant in $J/\psi \rightarrow N\bar{N}$ decay and the relative phase of between the strong and electromagnetic amplitudes is close to 90°
- In contrast, in $\psi(3686)$ decays, the branching fractions are quite close between the two decay modes, but the $\alpha$ values are not, which may imply a more complex mechanism in the decay of $\psi(3686) \rightarrow N\bar{N}$. It makes a similar and straight forward extraction of the phase angle impossible in the decay of $\psi(3686) \rightarrow N\bar{N}$, and further studies are deserved.

Observation of $\psi(3686) \rightarrow n\bar{n}$ and improved measurement of $\psi(3686) \rightarrow p\bar{p}$


- $Br(\psi(3686) \rightarrow n\bar{n}) = (3.06 \pm 0.06 \pm 0.14) \times 10^{-4}$
- $\alpha_{n\bar{n}} = 0.68 \pm 0.12 \pm 0.11$
- $Br(\psi(3686) \rightarrow p\bar{p}) = (3.05 \pm 0.20 \pm 0.12) \times 10^{-4}$
- $\alpha_{p\bar{p}} = 1.03 \pm 0.06 \pm 0.03$