Measuring $\psi'' \to \rho \pi$ in $e^+e^-$ experiment

P. Wang$^a$, C. Z. Yuan $^a$, X. H. Mo$^{a,b}$

$^a$Institute of High Energy Physics, P.O.Box 918, Beijing 100039, China

$^b$China Center of Advanced Science and Technology, Beijing 100080, China

In $S$- and $D$-wave mixing scheme, the branching ratio of $\psi'' \to \rho \pi$ is estimated. Together with the continuum cross section of $\rho \pi$ estimated by form factor, the observed cross section of $\rho \pi$ production at $\psi''$ in $e^+e^-$ experiment is calculated taking into account the interference effect between the resonance and continuum amplitudes and the initial state radiative correction. The behavior of the cross section reveals that the disappearance of $\rho \pi$ signal just indicates the existence of the corresponding branching ratio $B_{\psi'' \to \rho \pi}$ at the order of $10^{-4}$.

1. Introduction

The lowest charmonium resonance above the charmed particle production threshold is $\psi(3770)$ (shortened as $\psi'$) which provides a rich source of $D^0\overline{D}^0$ and $D^+D^-$ pairs, as anticipated theoretically [1]. However, non-$D\overline{D}$ (non-charmed final state) decay of $\psi''$ was studied theoretically and searched experimentally almost two decades ago. The OZI violation mechanism [2] was utilized to understand the possibility of non-$D\overline{D}$ decay of $\psi''$ [3], and experimental investigations involving noncharmed decay modes could be found in Ref. [4].

To explain the large $\Gamma_{\psi''}$, it is suggested [5] that the mass eigenstates $\psi(3686)$ (shortened as $\psi''$) and $\psi'$ are the mixtures of the $S$- and $D$-wave of charmonia, namely $\psi(2^3S_1)$ state and $\psi(1^3D_1)$ state. Recently it is proposed that such mixing gives possible solution to the so-called “$\rho\pi$ puzzle” in $\psi'$ and $J/\psi$ decays [7]. In this scheme

$$\langle \rho \pi | \psi' \rangle = \langle \rho \pi | 2^3S_1 \rangle \cos \theta - \langle \rho \pi | 1^3D_1 \rangle \sin \theta ,$$

$$\langle \rho \pi | \psi'' \rangle = \langle \rho \pi | 2^3S_1 \rangle \sin \theta + \langle \rho \pi | 1^3D_1 \rangle \cos \theta ,$$

(1)

where $\theta$ is the mixing angle between pure $\psi(2^3S_1)$ and $\psi(1^3D_1)$ states and is fitted from the leptonic widths of $\psi''$ and $\psi'$ to be either $(-27 \pm 2)^\circ$ or $(12 \pm 2)^\circ$ [4]. The latter value of $\theta$ is consistent with the coupled channel estimates [5,6] and with the ratio of $\psi'$ and $\psi''$ partial widths to $J/\psi$ [$\rho\pi$] is $0.9$. Hereafter, the discussions in this Letter are solely for the mixing angle $\theta = 12^\circ$.

If the mixing and coupling of $\psi'$ and $\psi''$ lead to complete cancellation of $\psi' \to \rho \pi$ decay ($\langle \rho \pi | \psi' \rangle = 0$), the missing $\rho \pi$ decay mode of $\psi'$ shows up instead as decay mode of $\psi''$, enhanced by the factor $1/\sin^2 \theta$. For $\theta = 12^\circ$, the $\psi''$ decay branching ratio [7]

$$B_{\psi'' \to \rho \pi} = (4.1 \pm 1.4) \times 10^{-4} .$$

(2)

With the resonance parameters of $\psi''$ from PDG2002 [10], the total resonance cross section of $\psi''$ production at Born order is

$$\sigma_{\psi'' \to e^+e^-} = \frac{12\pi}{M_{\psi''}} \cdot B_{ee} = (11.6 \pm 1.8) \text{ nb} .$$

Here $M_{\psi''}$ and $B_{ee}$ are the mass and $e^+e^-$ branching ratio of $\psi''$. With Eq. (2), the Born order cross section of $\psi'' \to \rho \pi$ is

$$\sigma_{\psi'' \to \rho \pi} = (4.8 \pm 1.9) \text{ pb} .$$

It is known that at $\sqrt{s} = M_{\psi''}$, the total continuum cross section, which is 13 nb, is larger than that of resonance. Due to the OZI suppression, the total cross section of non-$D\overline{D}$ decay from the resonance is much smaller than that from the continuum. For an individual exclusive mode, the contribution from the continuum process may be larger than or comparable with that from the resonance decay. For the $\rho \pi$ mode, the cross section
of the resonance decay is more than three orders of magnitude smaller than the total continuum cross section, thus the contribution from the continuum and the corresponding interference effect must be studied carefully and taken into account in case of significant modification of the experimentally observed cross section.

In the following sections, the Born order cross sections from the continuum and the resonance decays are given by virtue of the form factor and the $S$- and $D$-wave mixing model, then the experimental observable is calculated taking into account the radiative correction and experimental conditions. Finally the dependence of the observed $\rho\pi\gamma$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.

2. Born order cross section of $\rho\pi$

In $e^+e^-$ annihilation experiment at the charmonium resonance $\psi''$, there are three amplitudes responsible for $\rho^0\pi^0$ final state:\footnote{Generally for certain final state $f$, three amplitudes describe the following three processes:}

\begin{align*}
A_{\rho^0\pi^0}(s) &= a_{3g}(s) + a_\gamma(s) + a_c(s) \\
A_c(s) &= F_{\rho^0\pi^0}(s) \\
A_\gamma(s) &= B(s) \cdot F_{\rho^0\pi^0}(s) ,
\end{align*}

As to electromagnetic interaction, the $a_c$ and $a_\gamma$ are related to the $\rho\pi$ form factor:

\begin{align*}
a_c(s) &= F_{\rho^0\pi^0}(s) \\
a_\gamma(s) &= B(s) \cdot F_{\rho^0\pi^0}(s) ,
\end{align*}

with the notation

\[ B(s) \equiv \frac{3\sqrt{8T_{cc}/\alpha}}{s - M_{\psi''}^2 + iM_{\psi''}\Gamma_1} , \]

where $\alpha$ is the QED fine structure constant, $\Gamma_1$ and $\Gamma_{cc}$ are the total width and $e^+e^-$ partial width of $\psi''$. The strong decay amplitude can be parametrized in terms of its relative phase ($\phi$) and relative strength ($C$) to the electromagnetic decay amplitude:

\[ a_{3g}(s) = Ce^{i\phi}a_\gamma(s) , \]

where $C$ is taken to be real.

Using $C$, $\phi$ and $F_{\rho^0\pi^0}$, $A_{\rho^0\pi^0}$ becomes\footnote{Hereafter $\rho^0\pi^0$ is used for one of the three different $\rho\pi$ isospin states, and $\rho\pi$ for the sum of them.}

\[ A_{\rho^0\pi^0}(s) = [(Ce^{i\phi} + 1)B(s) + 1] \cdot F_{\rho^0\pi^0}(s) , \]

so the total $\rho^0\pi^0$ cross section at Born order is

\[ \sigma_{\rho^0\pi^0}^{Born}(s) = \frac{4\pi\alpha^2}{3M_{\rho^0}^2} |A_{\rho^0\pi^0}(s)|^2 q_{\rho^0\pi^0}^3 , \]

where $q_{\rho^0\pi^0}$ is the three momentum of $\rho^0$ or $\pi^0$ in the final state.

Since there is no experimental information on $\rho\pi$ cross section for the continuum process at resonance peak, the $\omega\pi^0$ form factor is used for estimation. According to the SU(3) symmetry\footnote{In case of significant modification of the experimental conditions. Finally the dependence of the observed $\rho\pi\gamma$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.}

\[ F_{\rho^0\pi^0}(s) = \frac{1}{3} F_{\omega\pi^0}(s) . \]

$F_{\omega\pi^0}$ is measured at $\sqrt{s} = M_{\psi''}$ to be\footnote{In case of significant modification of the experimental conditions. Finally the dependence of the observed $\rho\pi\gamma$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.}

\[ \left| \frac{F_{\omega\pi^0}(M_{\psi''}^2)}{F_{\omega\pi^0}(0)} \right| = (1.6 \pm 0.4) \times 10^{-2} . \]

This is in good agreement with the model dependent calculation in Ref.\footnote{In case of significant modification of the experimental conditions. Finally the dependence of the observed $\rho\pi\gamma$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.}

\[ \left| \frac{F_{\omega\pi^0}(s)}{F_{\omega\pi^0}(0)} \right| = \frac{(2\pi f_\pi)^2}{3s} , \]

where $f_\pi$ is the pion decay constant, or

\[ \left| F_{\omega\pi^0}(s) \right| = \frac{0.531 \text{ GeV}}{s} , \]

by using the $\omega\pi^0$ form factor at $Q^2 = 0$ from the crossed channel decay $\omega \rightarrow \gamma\pi^0$.

With the form factor in Eq. (5), the Born order continuum cross section of $\rho\pi$ production at $\psi''$ resonance peak is\footnote{In case of significant modification of the experimental conditions. Finally the dependence of the observed $\rho\pi\gamma$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.}

\[ \sigma_{\rho^0\pi^0}^{Born}(s) = 4.4 \text{ pb} . \]
For the resonance part, 
\[ |(C e^{i\phi} + 1) F_{\rho \pi^0}(M_{\psi''}^2) |^2 \Gamma_{\rho \pi^0}^Q M_{\psi''}^2 = |\langle \rho^0 | \rho' \rangle |^2 , \]
where \( \Gamma_{\rho \pi^0}^Q \) is the \( e^+ e^- \) partial width without vacuum polarization correction. Starting from Eq. (1), it can be acquired
\[ \langle \rho^0 | \rho' \rangle = \langle \rho^0 | \rho' \rangle \frac{2\Gamma_{\rho \pi^0}^Q M_{\psi''}^2}{\sin \theta} \]
Since there could be an unknown phase between \( \langle \rho^0 | \rho' \rangle \) and \( \langle \rho^0 | \rho' \rangle \), or equivalently a phase (denoted as \( \alpha \)) between \( \langle \rho^0 | \rho' \rangle \) and \( \langle \rho^0 | \rho' \rangle \), \( \langle \rho^0 | \rho' \rangle \) is constrained in a range. With model-dependent estimation \( B_{\psi'' \to \rho \pi} = (1.11 \pm 0.87) \times 10^{-4} \) and \( \langle \rho^0 | \rho' \rangle \) in Ref. [22], for \( \theta = 12^\circ \),
\[ \langle \rho^0 | \rho' \rangle = (1.8 \sim 5.2) \times 10^{-5} \text{ GeV} , \]
or equivalently
\[ B_{\psi'' \to \rho \pi} = (2.5 \sim 7.2) \times 10^{-4} \]
which corresponds to the variation of \( \alpha \) from 0\(^\circ\) to 180\(^\circ\). So the relation between \( C \) and \( \phi \) could be derived from Eq. (4).

For a given \( B_{\psi'' \to \rho \pi} \), according to Eqs. (4) and (5), the observed cross section depends on the interference pattern between the continuum one-photon amplitude and the \( \psi'' \) decay amplitude. In case of \( \phi = \pm 90^\circ \), the maximum constructive or destructive interference between \( a_{\rho \pi} \) and \( a_{\gamma} \) happens at the resonance peak; while \( \phi = 0^\circ \) or 180\(^\circ\) leads to constructive or destructive interference between \( a_{\rho \pi} \) and \( a_{\gamma} \).

3. Observed cross section of \( \rho \pi \)

Due to the rapidly varying Breit-Wigner formula and the \( \rho \pi \) form factor as the center of mass energy changes, the observed cross section depends strongly on the initial state radiative correction which reduces the center of mass energy, and the invariant mass cut \( (m_{cut}) \) which removes the events produced by the initial state radiation. Taking these into account, the observed cross section becomes
\[ \sigma^{obs}(s) = \int_0^{x_m} dxF(x, s) \frac{\sigma^{Born}(s(1-x))}{|1 - \Pi(s(1-x))|^2} , \]
where
\[ x_m = 1 - m_{cut}^2/s . \]

\( F(x, s) \) has been calculated to the accuracy of 0.1\% and \( \Pi(s) \) is the vacuum polarization factor.

It should be emphasized that the radiative correction modifies the Born order cross section in a profound way. Firstly, it shifts upward the maximum total cross section to the energy \( M_{\psi''} + 0.75 \text{ MeV} \). Secondly, the radiative correction changes the Born order cross section significantly. For example, if \( \phi = -90^\circ \) and \( B_{\psi'' \to \rho \pi} = 4.1 \times 10^{-4} \), \( \sigma^{Born_{3/2}} = 5.6 \times 10^{-3} \text{ pb} \), after radiative correction \( \sigma^{obs_{3/2}} = 0.31 \text{ pb} \) for \( x_m = 0.02 \).

The dependence of the observed cross section on the invariant mass cut is illustrated in Fig. 1, for the branching ratio in Eq. (4) and \( \phi = -90^\circ \). It is obvious that a tighter invariant mass cut results in a smaller observed cross section. In the following analysis, \( x_m = 0.02 \) is taken, which means a cut of \( \rho \pi \) invariant mass within 38 MeV from \( M_{\psi''} \), or, near the median between \( \psi' \) and \( \psi'' \) masses.

It is worth while to notice the variation of the observed \( \rho \pi \) cross section with the phase \( \alpha \) between \( \langle \rho | \rho' \rangle \) and \( \langle \rho | \rho' \rangle \). When \( \alpha \) varies from 0\(^\circ\) to 180\(^\circ\), \( \sigma^{obs}_{3/2} \) in Fig. 1 moves from the line for \( B_{\psi'' \to \rho \pi} = 2.5 \times 10^{-4} \) to that for \( B_{\psi'' \to \rho \pi} = 4.1 \times 10^{-4} \), and then increases to that for \( B_{\psi'' \to \rho \pi} = 7.2 \times 10^{-4} \), at a specific invariant mass cut.

The phase \( \phi \) between \( a_{\rho \pi} \) and \( a_{\gamma} \) has significant effect on the observed cross section due to different interference patterns. Fig. 1(a) shows the observed cross sections at \( \psi'' \) resonance peak as functions of \( B_{\psi'' \to \rho \pi} \) with \( x_m = 0.02 \) and \( \phi = -90^\circ \), 90\(^\circ \), 0\(^\circ\) and 180\(^\circ\), respectively. For the destructive interference between \( a_{\rho \pi} \) and \( a_{\gamma} \) (\( \phi = -90^\circ \)), the cross section reaches its minimum for \( B_{\psi'' \to \rho \pi} \approx 4.1 \times 10^{-4} \), which corresponds to the resonance cross section of 3.3 pb, but \( \sigma^{obs}_{3/2} \) is only 0.31 pb, an order of magnitude smaller.

Above calculations of the observed cross section

\(^{4}\)In this Letter, it is assumed that the experiments take data at the energy which yields the maximum total cross section. The observed cross sections are calculated at this energy instead of the nominal resonance mass.
could be extended to other $1^{-0^{-}}$ decay modes, such as $K^{*0}K^0 + c.c.$ and $K^{*+}K^- + c.c.$, whose amplitudes are expressed as\cite{12}:

$$A_{K^{*0}K^0} = [(CRe^{i\phi} - 2)B(s) - 2|\mathcal{F}_{\rho\pi\eta}(s)],$$

$$A_{K^{*+}K^-} = [(CRe^{i\phi} + 1)B(s) + 1|\mathcal{F}_{\rho\pi\eta}(s)],$$

where $\mathcal{R} \equiv (a_{3g} + \epsilon)/a_{3g}$, with $\epsilon$ describing the SU(3) breaking effect. It is assumed that $\epsilon$ has the same phase as $a_{3g}$\cite{22}, so $\mathcal{R}$ is real. Using $\mathcal{C}$ determined from $B_{\psi'\rightarrow\rho\pi}$ and $\mathcal{R} = 0.775$ from fitting $J/\psi \rightarrow 1^{-0^{-}}$ decay\cite{12}, the cross section of $K^{*0}K^0$ or $K^{*+}K^-$ is calculated by Eq. (4) merely with the substitution of $A_{K^{*0}K^0}$ or $A_{K^{*+}K^-}$ for $A_{\rho\pi\eta}$. Their observed cross sections at $\psi''$ resonance peak as functions of $B_{\psi''\rightarrow\rho\pi}$ are shown in Fig. 2(b) for $\phi = -90^\circ$ and $x_m = 0.02$. It could be seen that the cross section of $K^{*0}K^0 + c.c.$ is much larger than those of $\rho\pi$ and $K^{*+}K^- + c.c.$ in a wide range of the $\rho\pi$ branching ratio.

Since the data at $\psi''$ resonance peak alone can not fix all parameters ($C$, $\phi$, and $\mathcal{F}_{\rho\pi}$) in $B_{\psi''\rightarrow\rho\pi}$ determination, the correct way of measuring the branching ratio is through energy scan of the resonance. Fig. 3 shows the observed $\rho\pi$ cross section in the vicinity of the $\psi''$ resonance, with $x_m = 0.02$ and the branching ratio in Eq. (5) for four values of $\phi$: $-90^\circ$, $+90^\circ$, $0^\circ$, and $180^\circ$. The hatched areas are due to the variation of $\alpha$. For $\phi = 0^\circ$ or $180^\circ$, the maximum observed cross section is above or below the resonance mass. Only for $\phi = +90^\circ$ the maximum observed cross section is near the resonance peak. Here the most interesting phenomenon is, with $\phi = -90^\circ$, the observed cross section reaches its minimum near the resonance peak! This phenomenon suggests that at the resonance peak the undetectable experiment cross section of $\rho\pi$ just indicates the existence of the corresponding branching ratio at the order of $10^{-4}$.
modes, such as $K^0\pi^0$ and $K^{*-}\overline{K}^0$. That is, if the interference between $a_{3g}$ and $a_e$ for $\rho\pi$ is destructive, then such interference is just constructive for $K^{*0}\overline{K}^0+c.c.$ and vice versa. In the resonance scan, if $\sigma_{obs}^{\rho\pi}$ reaches its valley near $\psi''$ resonant mass, $\sigma_{obs}^{\rho\pi, K^{*0}\overline{K}^0+c.c.}$ reaches its peak. This means if the observed $\rho\pi$ cross section at $\psi''$ is smaller than that at continuum, the observed $K^{*0}\overline{K}^0+c.c.$ cross section at $\psi''$ will be larger. So the measurements of $K^{*0}\overline{K}^0+c.c.$ and $\rho\pi$ provide a crucial test of the interference pattern between $a_{3g}$ and $a_e$.

There are theoretical arguments in favor of the orthogonality between $a_{3g}$ and $a_{\gamma}$ of the charmonium decays. The phenomenological analyses for many two-body decay modes: $1^-0^-$, $0^-0^-$, $1^-1^-$, $1^+0^-$, and Nucleon anti-Nucleon on $J/\psi$ data support this assumption. The recent analysis of $\psi' \to 1^-0^-$ decays also favors the orthogonal phase. For $\psi''$, it is of great interest here to note the search of $\rho\pi$ mode by MARK-III [4] at the $\psi''$ peak. The result corresponds to the upper limit of the $\rho\pi$ production cross section of 6.3 pb at 90% C. L., which favors $\phi = -90^\circ$ than other possibilities as seen from Fig. 3. These experimental information suggests the phase $\phi = -90^\circ$ between $a_{3g}$ and $a_e$ be universal for all quarkonia decays.

At last, a few words about the effect of the beam energy spread $\Delta$ for cross section measurement [13]. $\psi''$ is a relatively wide resonance, for a collider with small energy spread, such as $\Delta = 1.4$ MeV at BES/BEPC [20], this effect is negligible. With increasing $\Delta$, the correction becomes larger. For example, on a collider with $\Delta = 5$ MeV, for $\phi = -90^\circ$ and $x_m = 0.02$, the observed cross section of $\rho\pi$ for $B_{\psi''-\rho\pi} = 4.1 \times 10^{-4}$ is more than doubled to 0.68 pb comparing with the value without energy spread effect.

\[5\text{In Fig. 3 if the scan behavior of } \sigma_{obs}^{\rho\pi} \text{ is similar to the curve corresponding to } \phi = -90^\circ, \sigma_{obs}^{\rho\pi, K^{*0}\overline{K}^0+c.c.} \text{ would be similar to the } \rho\pi \text{ curve corresponding to } \phi = +90^\circ.\]
5. Summary

By virtue of S- and D-wave mixing model, $B_{\psi'' \rightarrow \rho\pi}$ is estimated, together with the estimated $\sigma_{e^+e^- \rightarrow \rho\pi}$ by form factor, the observed $\rho\pi$ cross section at $\psi''$ in $e^+e^-$ experiment, which takes into account the initial state radiative correction, has been calculated. The study shows that the disappearance of $\rho\pi$ cross section at $\psi''$ peak just indicates the branching ratio of $\psi'' \rightarrow \rho\pi$ at the order of $10^{-4}$.

Besides the information of $\psi''$, if the phase analyses of $J/\psi$ and $\psi'$ are also taken into consideration, it is natural to conclude that the phase $\phi = -90^\circ$ between $a_3g$ and $a_\gamma$ is universal for all quarkonia decays.

In the forthcoming high luminosity experiments of $\psi''$ at CLEO-c [27] and BES-III [28], the property of $\rho\pi$ decay and the feature of the phase are expected to be tested quantitatively.

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