Evidence for the decay $\psi(3770) \rightarrow K^+K^-$

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Existing data on the $e^+e^- \rightarrow K^+K^-$ cross section at the center-of-mass energy above 2.6 GeV are fitted with a sum of $\psi(3770)$ resonant and continuum contributions. Two solutions for the resonance production cross section are found with a significance of 3.2$\sigma$. Data on the $e^+e^- \rightarrow K_SK_L$ cross section are used to resolve the ambiguity and for further constraining the values of the $e^+e^- \rightarrow \psi(3770) \rightarrow K^+K^-$ cross section and the interference phase. They are found to be $\sigma_{\psi(3770)} = 0.073^{+0.061}_{-0.044}$ pb and $\phi = (309^{+17}_{-9})^\circ$, respectively. The same fitting procedure for the $\psi(4160)$ resonance leads to the upper limit on the $e^+e^- \rightarrow \psi(4160) \rightarrow K^+K^-$ cross section $\sigma_{\psi(4160)} < 0.062$ pb at 90\% confidence level.

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I. INTRODUCTION

The $\psi(3770)$ meson is the lowest-mass $c\bar{c}$ state lying above the open-charm threshold and therefore is expected to decay predominantly into $D\bar{D}$ pairs. A simple estimation based on the assumption that the decay probability for $c\bar{c}$-meson into light hadrons is proportional to $|\Psi(0)|^2$, where $\Psi(0)$ is the meson wave function at the origin, leads to the relation between $\psi(3770)$ and $\psi(2S)$ branching fractions:

\[
B(\psi(3770) \rightarrow f) \approx B(\psi(2S) \rightarrow f) \frac{B(\psi(3770) \rightarrow e^+e^-)}{B(\psi(2S) \rightarrow e^+e^-)} \approx 10^{-3} B(\psi(2S) \rightarrow f)
\] (1)

The total branching fraction of the $\psi(3770)$ into light hadrons is expected to be about $10^{-3}$. This prediction strongly contradicts the BES Collaboration observation that the total branching fraction for non-$D\bar{D}$ decays is $(14.5 \pm 1.7 \pm 5.8)\%$ \(^3\). The CLEO measurement of the same value is $B(\psi(3770) \rightarrow non-D\bar{D}) < 9\%$ at 90\% confidence level (CL) \(^4\). The BES measurement has triggered an intensive search for $\psi(3770)$ decays into light hadrons. About 90 final states were studied \(^3\), but only two decays, to $\phi\eta$ \(^4\) and $p\bar{p}$ \(^5\), were observed. The measured branching fractions significantly exceed above prediction, by more than an order of magnitude for $\psi(3770) \rightarrow p\bar{p}$ and by four orders for $\psi(3770) \rightarrow \phi\eta$ decay. The mechanism explaining relatively large values of branching fractions is production of light hadrons via intermediate $D\bar{D}$ loops (see Refs. \(^4\) \(^5\) and references therein). The predicted in Ref. \(^4\) branching fraction for the decay $\psi(3770) \rightarrow K^+K^-$, studied in this work, is $9 \times 10^{-5}$; it is larger than the prediction of Eq. (1) by about three orders of magnitude.

For $\psi(3770)$ branching fractions of $10^{-4}$, the cross section for the resonant process $e^+e^- \rightarrow \psi(3770) \rightarrow f$ is usually less than the nonresonant $e^+e^- \rightarrow f$ cross section. Therefore, the $\psi(3770)$ decay will reveal itself as an interference pattern in the energy dependence of the $e^+e^- \rightarrow f$ cross section. The first experimental study of the interference near the $\psi(3770)$ resonance was performed for the $e^+e^- \rightarrow p\bar{p}$ process in the BESIII experiment \(^6\). In this work existing data on the $e^+e^- \rightarrow K^+K^-$ and $e^+e^- \rightarrow K_SK_L$ cross sections are used to study the interference near the $\psi(3770)$ and $\psi(4160)$ resonances and measure the cross sections for the resonant processes $e^+e^- \rightarrow \psi(3770), \psi(4160) \rightarrow K^+K^-$. (See Fig. 1).

\[\text{FIG. 1: The } e^+e^- \rightarrow K^+K^- \text{ cross section multiplied by the factor } (E(\text{GeV})/3.772)^6 \text{ measured in the works: } \bullet \text{ (BABAR), } \nabla \text{ (CLEO), and } \blacktriangle \text{ (Seth et al). Data of Refs. } 3, 4 \text{ are approximated by Eq. } 2. \text{ The inset shows an enlarged version of the energy region near the resonance } \psi(3770).\]

II. FIT TO THE $e^+e^- \rightarrow K^+K^-$ CROSS SECTION

For the $e^+e^- \rightarrow K^+K^-$ process, we use the BABAR measurements in the center-of-mass energy region $E = 2.6 - 7.5$ GeV obtained using the initial-state radiation (ISR) method \(^8\), and direct measurements \(^9\) \(^10\) at
\[ E = 3.671, 3.772, 4.17 \text{ based on data collected in the CLEO experiment.} \]

The measured energy dependence of the \( e^+e^- \rightarrow K^+K^- \) cross section above 2.6 GeV is shown in Fig. 1. The curve is the result of the fit to the cross-section data with the function proposed in Ref. [8]:

\[
\sigma_{\text{cont}}(E) = \frac{\alpha^2 \beta^3}{3E^2} |F_K(E)|^2,
\]

\[
|F_K(E)| = \frac{A}{E^2(\gamma + B)},
\]

where \( \alpha \) is the fine-structure constant, \( \beta = \sqrt{1 - 4m_K^2/E^2} \), \( m_K^2 \) is the charged kaon mass, \( A, B, \) and \( \gamma \) are fitted parameters. The measurements from Ref. [10] performed near the maxima of the \( \psi(3770) \) and \( \psi(4160) \) resonances, are not included in the fit.

As seen in the inset, the point at 4.17 GeV is consistent with the approximation of the nonresonant cross section, whereas the point at 3.772 GeV lies about three standard deviations below. The deviation may be a result of interference between the resonant and nonresonant amplitudes of the \( e^+e^- \rightarrow K^+K^- \) reaction.

The cross section near the \( \psi(3770) \) resonance is described by the following formula:

\[
\sigma_{K+K^-}(E) = \left| \sqrt{\sigma_{\text{cont}}} - \sqrt{\sigma_{\text{cont}}^\psi \sigma_{\psi}^\phi} \right|^2 D^2 + \sigma_{\text{cont}} \sigma_{\psi}^\phi \sin \phi \frac{m_{\psi}^2 \Gamma_{\psi}^\phi}{|D|^2} - 2\sqrt{\sigma_{\text{cont}} \sigma_{\psi}^\phi} \cos \phi \frac{m_{\psi} \Gamma_{\psi} (m_{\psi}^2 - E^2)}{|D|^2},
\]

where \( \sigma_{\psi} = \sigma_{\psi(3770)} \) is the cross section for the process \( e^+e^- \rightarrow \psi(3770) \rightarrow K^+K^- \) in the resonance maximum, \( \phi \) is the relative phase between resonant and nonresonant amplitudes, \( D = m_{\psi}^2 - E^2 - im_{\psi} \Gamma_{\psi} \), and \( m_{\psi} \) and \( \Gamma_{\psi} \) are the \( \psi(3770) \) mass and width, respectively.

Data from Refs. [8, 9] and the measurement at \( E = 3.772 \text{ GeV} \) from Ref. [10] are fitted by the formula (3). The measurements in Ref. [8] were made using the ISR method. Therefore, they are compared with the average cross-section values over the corresponding energy intervals. For the energy intervals near the \( \psi(3770) \) resonance, 3.6–3.8 and 3.8–4.0 GeV, where the \( e^+e^- \rightarrow K^+K^- \) cross section changes rapidly due to interference of resonant and nonresonant amplitudes, the \( K^+K^- \) invariant mass spectrum for the ISR process \( e^+e^- \rightarrow K^+K^- \gamma \) is used instead of the cross section. The mass spectrum is described as follows

\[
\frac{dN}{dM^*} = \int R(M^*,M) \frac{dN}{dM}(M) dM - \frac{dN}{dM^*}_{\text{bkg}},
\]

\[
\frac{dN}{dM} = \sigma_{K+K^-}(M) \frac{dL}{dM}(M) \varepsilon(M),
\]

where \( M \) and \( M^* \) are the true and measured \( K^+K^- \) invariant masses, respectively, \( R(M^*,M) \) is a function describing detector mass resolution \( \varepsilon \), \( dL/dM \) is the ISR luminosity (see, for example Ref. [8]), \( \varepsilon \) is the detection efficiency, \( (dN/dM^*)_{\text{bkg}} \) is the mass spectrum of background events. The mass dependence of the ISR luminosity, detection efficiency and \( (dN/dE_{\text{meas}})_{\text{bkg}} \) are obtained by interpolation between the values given in Ref. [8] for mass intervals shown in Fig. 1. The experimental mass spectrum contains also events from the decay \( \psi(2S) \rightarrow K^+K^- \). The \( \psi(2S) \) contribution is added to the fit with a shape described by convolution of a Breit-Wigner resonance line-shape with the resolution.
function. The measured cross and the mass spectrum are fitted simultaneously.

The systematic uncertainty of the cross section measured in Ref. [8] is separated into two parts. The first includes systematic errors of statistical origin, mainly due to background subtraction. This uncertainty is added in quadrature to the statistical error of the cross section. The second part includes correlated uncertainties due to the data-MC simulation difference in the detection efficiency and luminosity determination. This uncertainty ($\sigma_S$) is practically independent of energy and is equal to 2.4%. In the fit, it is taken into account by multiplying the theoretical cross section [Eq. (2)] for the BABAR measurements by a free parameter $S$, and by adding to the logarithmic likelihood function the term $(S - 1)^2/(2\sigma_S^2)$, which allows all theoretical values for the BABAR measurements to be shifted simultaneously inside $\sigma_S$. For the measurements of Refs. [9, 10] at $E = 3.671$ and 3.772 GeV, the statistical and systematic uncertainties are added in quadrature.

The fitted parameters are $\sigma_0$, $\phi$, the value of the nonresonant cross section at $E = 3.772$ GeV, $\gamma$ and $B$ from Eq. (2), the number of events from the $\psi(2S) \rightarrow K^+K^-$ decay, and $S$. The result of the fit is shown in Fig. 2 by dashed curves. The statistical significance of the $\psi(3770) \rightarrow K^+K^-$ decay is calculated from the differences of the likelihood function values for the fits with free $\sigma_0$ and $\sigma_0 = 0$ and is found to be 3.2$\sigma$.

The fit yields two solutions. They correspond to the same values of the factors $\sigma_0 + 2\sqrt{\sigma_{cont}\sigma_0}\sin\phi$ and $2\sqrt{\sigma_{cont}\sigma_0}\cos\phi$ in Eq. (3), but different values of $\sigma_0$ and $\phi$. The 1$\sigma$ contours for these solutions are shown in Fig. 3.

To determine the branching fraction the fitted cross section is divided by the $e^+e^- \rightarrow \psi(3770)$ cross section, which is calculated as $\sigma_0 = (12\pi/m_{\psi}^2)\Gamma(\psi(3770) \rightarrow e^+e^-)/\Gamma(\psi)$. Unfortunately, the experimental situation with $\psi(3770)$ electron width is somewhat uncertain. The Particle Data Group [3] value $\Gamma(\psi(3770)) = 0.262 \pm 0.018$ keV corresponds to $\sigma_0 \approx 9.9 \pm 0.8$ nb, which is significantly higher than the value of the $e^+e^- \rightarrow D\bar{D}$ cross section ($6.57 \pm 0.04 \pm 0.10$ nb) measured by the CLEO Collaboration in the maximum of the $\psi(3770)$ resonance [11]. Interference between resonant and nonresonant amplitudes in the $e^+e^- \rightarrow D\bar{D}$ reaction, which was ignored in most $\Gamma(\psi(3770) \rightarrow e^+e^-)$ measurements, is a source of additional uncertainty. The analysis performed by the KEDR collaboration [12] shows that taking into account the interference decreases $\Gamma(\psi(3770) \rightarrow e^+e^-)$ by about 40% compared with the value obtained ignoring the interference. In this paper we will estimate the $\psi(3770) \rightarrow K^+K^-$ branching fraction using the value $\sigma_0 = 6.36 \pm 0.87^{+0.41}_{-0.30}$ nb obtained by CLEO [13]. The close value was used previously in the measurements of $B(\psi(3770) \rightarrow \phi\eta)$ [4] and $B(\psi(3770) \rightarrow K_SK_L)$ [14].

The two obtained solutions correspond to the branching fractions of about $10^{-4}$ and $3 \times 10^{-3}$. The latter significantly, more than by an order of magnitude, exceeds theoretical predictions [3].

III. CONSTRAINTS FROM $e^+e^- \rightarrow K_SK_L$ MEASUREMENTS

Additional constraints on the $B(\psi(3770) \rightarrow K^+K^-)$ value can be obtained from data on the $e^+e^- \rightarrow K_SK_L$ process. The branching fractions of $\psi(3770) \rightarrow K^+K^-$ and $\psi(3770) \rightarrow K_SK_L$ may be different only due to single-photon contributions, which are related to the values of the nonresonant $e^+e^- \rightarrow K^+K^-$ and $e^+e^- \rightarrow K_SK_L$ cross sections. The cross section for the single-photon transition $e^+e^- \rightarrow \psi(3770) \rightarrow \gamma^* \rightarrow K^+K^-$ is calculated as [15]

$$\sigma_{\psi,\gamma} = \frac{9B(\psi(3770) \rightarrow e^+e^-)^2}{\alpha^2 \sigma_{cont}(m_\psi)} \quad (6)$$

and is about $3 \times 10^{-5}$ pb. The corresponding branching fraction is about $0.5 \times 10^{-8}$. For the $K_SK_L$ final state, the single-photon branching fraction is expected to be at least an order of magnitude smaller (see discussion below). Taking into account interference between electromagnetic and strong decay amplitudes, we conclude that for $B(\psi(3770) \rightarrow K^+K^-)$ higher than $10^{-6}$ the single-photon contribution is negligible. Therefore, we expect that $B(\psi(3770) \rightarrow K^+K^-) = B(\psi(3770) \rightarrow K_SK_L)$ is good approximation.

For the $e^+e^- \rightarrow K_SK_L$ process, there is an upper limit on the cross section at 3.773 GeV [14]: $\sigma_{K_SK_L}(m_\psi) < 0.07$ pb at 90% CL. In Ref. [14] this value was used to obtain the upper limit on $B(\psi(3770) \rightarrow K_SK_L)$. This
approach, however, does not take into account interference between resonant and nonresonant amplitudes of the $e^+e^- \to K_SK_L$ process. Data on the nonresonant cross section in the energy region of interest are practically absent. There are two $e^+e^- \to K_SK_L$ measurements \[16, 17\] near 2 GeV. Comparing these measurements with data on the $e^+e^- \to K^+K^-$ cross section \[18\] we estimate that $r = \sigma_{K_SK_L}/\sigma_{K^+K^-} = 0.098 \pm 0.060$ at $E = 2$ GeV. At higher energy, there is only one measurement of this ratio at 4.17 GeV $r = 0.0144 \pm 0.0072$ \[19\], which may be distorted by resonance contributions from the $\psi(4160) \to K\bar{K}$ decays. The theoretical prediction for this ratio obtained using leading-order leading-twist QCD calculation of the kaon electromagnetic form factors, is $r \approx 0.04$ \[20\] in the energy region 3–4 GeV.

To take into account the $e^+e^- \to K_SK_L$ data, we include in the fit, described in the previous section, two additional measurements: $\sigma_{K_SK_L}(m_\psi) = 0.0 \pm 0.5$, which corresponds to the upper limit $\sigma_{K_SK_L}(m_\psi) < 0.07$ pb at 90\% CL, and $r(m_\psi) = 0.30 \pm 0.15$, obtained from a linear approximation between the $r$ values at $E = 2$ and 4.17 GeV. The energy dependence of the $e^+e^- \to K_SK_L$ cross section near $\psi(3770)$ resonance is described by Eq. \[3\] with the replacement of $\sigma_{cont}(E)$ by $r(m_\psi)\sigma_{cont}(E)$. It is expected that in the energy region under study the nonresonant $K^+K^-$ and $K_SK_L$ amplitudes have the same sign of the real parts and similar ratios of imaginary to real parts \[21\]. Therefore, we assume that the phase $\phi$ is the same for $e^+e^- \to K_SK_L$ and $e^+e^- \to K^+K^-$. The fit with the $K_SK_L$ data yields a single solution:

$$\sigma_{\psi(3770)} = 0.073^{+0.62}_{-0.44} \text{ pb,}$$  \hspace{1cm} (7)

$$\phi = (308^{+17}_{-34})^\circ.$$  \hspace{1cm} (8)

The $\sigma_\psi$ and $\phi$ values obtained with the $K_SK_L$ constraints are shifted from unconstrained values obtained in the previous section by about 1.5$\sigma$. The statistical significant of the result is the same, 3.2$\sigma$. The fitted energy dependence of the $e^+e^- \to K^+K^-$ cross section and the fitted mass spectrum are shown in Fig. \[2\] by the solid curves.

The fitted value of the nonresonant $e^+e^- \to K_SK_L$ cross section at $E = m_\psi$ is $0.117 \pm 0.062$ pb. The expected energy dependence of the $e^+e^- \to K_SK_L$ cross section near the $\psi(3770)$ resonance is shown in Fig. \[2\] by the solid curve. To study dependence of the result on the value of $r(m_\psi)$, the fit is performed with the $r$ values obtained at 2 GeV and 4.17 GeV, $r = 0.098 \pm 0.098$ and $r = 0.0144 \pm 0.0144$, respectively, taken with a 100\% uncertainty. The results for $\sigma_\psi$ and $\phi$ are changed insignificantly, while the value of the nonresonant $e^+e^- \to K_SK_L$ cross section decreases to $0.061 \pm 0.061$ pb. The energy dependence of the cross section obtained with modified $r(m_\psi)$ is shown in Fig. \[2\] by the dashed curve.

The branching fraction $\mathcal{B}(\psi(3770) \to K^+K^-)$ corresponding to the measured value of the resonant cross section is about $10^{-5}$. It is an order of magnitude lower than the prediction \[4\], but two orders larger than the estimation not taking into account effects of intermediate $D\bar{D}$ loops [Eq. \[1\]].

![FIG. 4: The expected from the fit energy dependence of the $e^+e^- \to K_S K_L$ cross section near the $\psi(3770)$ resonance. The solid and dashed curves correspond to different values of the nonresonant $e^+e^- \to K_S K_L$ cross section at $E = m_\psi$, 0.117 pb and 0.061 pb, respectively.](image)

### IV. UPPER LIMIT ON THE $\psi(4160) \to K^+K^-$ DECAY

The fitting procedure described above is used in the energy region of $\psi(4160)$ resonance. The BABAR \[8\] and CLEO \[9\] nonresonant $e^+e^- \to K^+K^-$ data, and the measurement of the $e^+e^- \to K^+K^-$ cross section at $E = 4.17$ GeV \[10\] (see Fig. \[1\]) are fitted together with the $e^+e^- \to K_SK_L$ cross section measurement, $\sigma_{K_SK_L} = 0.032 \pm 0.017$ pb at $E = 4.17$ GeV \[19\]. To estimate the nonresonant $e^+e^- \to K_SK_L$ cross section, the value of $r = 0.098 \pm 0.098$ is used in the fit. The fitted value of the $e^+e^- \to \psi(4160) \to K^+K^-$ cross section in the resonance maximum is found to be $\sigma_{\psi(4160)} = 0.006^{+0.047}_{-0.006}$. The corresponding upper limit is

$$\mathcal{B}(\psi(4160) < 0.062 \text{ pb at 90\% CL.}$$  \hspace{1cm} (9)

The $e^+e^- \to \psi(4160)$ cross section in the resonance maximum calculated from $\mathcal{B}(\psi(4160) \to e^+e^-) = (6.9 \pm 3.3) \times 10^{-6}$ \[3\] is equal to $5.8 \pm 2.8$ nb. Taking into account the uncertainty of the $\psi(4160)$ production cross section we estimate that $\mathcal{B}(\psi(3770) \to K^+K^-) < 2 \times 10^{-5}$ at 90\% CL.

### V. SUMMAR

Due to the relatively large continuum cross section for the $e^+e^- \to K^+K^-$ process, the $\psi(3770) \to K^+K^-$ and $\psi(4160) \to K^+K^-$ decays reveal themselves as interference patterns in the cross section energy dependence near the resonances. In this work, existing data on the
$e^+e^- \to K^+K^-$ and $e^+e^- \to K_SK_L$ cross sections [8–10, 14, 16, 19] have been analyzed to obtain the interference parameters. For $\psi(3770) \to K^+K^-$ decay, the $e^+e^- \to \psi(3770) \to K^+K^-$ cross section in the resonance maximum and the interference phase are found to be

$$\sigma_{\psi(3770)} = 0.073^{+0.62}_{-0.44} \text{ pb}, \quad \phi = (308^{+17}_{-34})^\circ,$$

with a statistical significance of 3.2σ. For the $\psi(4160) \to K^+K^-$ decay, the upper limit on the cross section in the resonance maximum has been obtained:

$$\sigma_{\psi(4160)} < 0.062 \text{ pb at 90\% CL.} \quad (12)$$

VI. ACKNOWLEDGMENTS

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