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Search for $K_S^0 K_L^0$ in ψ'' decays

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$K_S^0 K_L^0$ from ψ'' decays is searched for using the ψ'' data collected by BESII at BEPC, and the upper limit of the branching fraction is determined to be $\mathcal{B}(\psi'' \to K_S^0 K_L^0) < 2.1 \times 10^{-4}$ at 90% C.L. The measurement is compared with the prediction of the S- and D-wave mixing model of the charmonia, based on the measurements of the branching fractions of $J/\psi \to K_S^0 K_L^0$ and $\psi' \to K_S^0 K_L^0$.

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I. INTRODUCTION

From the perturbative QCD (pQCD), it is expected that both J/ψ and ψ' decaying into light hadrons are dominated by the annihilation of $c\bar{c}$ into three gluons or a virtual photon, with widths proportional to the square of

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the wave function at the origin [1]. This yields the pQCD "12% rule," that is

$$Q_h = \frac{\mathcal{B}_{\psi' \to h}}{\mathcal{B}_{J/\psi \to h}} = \frac{\mathcal{B}_{\psi' \to e^+e^-}}{\mathcal{B}_{J/\psi \to e^+e^-}} \approx 12\%.$$

Following the first observation of its violation in $\rho\pi$ and $K^{*+}K^- + \text{c.c.}$ modes by Mark II [2], BES has measured many two-body modes of ψ' decays, among which some obey the 12% rule while others violate it [3]. There have been many theoretical efforts in trying to solve the puzzle [4], however, none explains all the existing experimental data satisfactorily and naturally.

A most recent explanation of the "$\rho\pi$ puzzle" using the S- and D-wave charmonia mixing was proposed by Rosner [5]. In this scheme, the mixing of $\psi(2^3S_1)$ state and $\psi(1^3D_1)$ is in such a way which leads to almost complete cancellation of the decay amplitude of $\psi' \to \rho\pi$ and enhanced decay rate of ψ''. A study on the measurement of $\psi'' \to \rho\pi$ in e^+e^- experiments shows that with the decay rate predicted by the S- and D-wave mixing, the interference between the three-gluon decay amplitude of the ψ'' and the continuum one-photon amplitude is destructive so the observed cross section is very small [6], which is in agreement with the upper limit of the $\rho\pi$ cross section at the ψ'' peak by Mark III [7]. Although this needs to be further tested by a high luminosity experiment operating at the ψ'' mass energy, such as CLEOc [8], it already implied that $\mathcal{B}(\psi'' \to \rho\pi)$ is most probably at the order of 10^{-4}, in agreement with the prediction of the S- and D-wave mixing schemes.

If the S- and D-wave mixing is the key for solving the $\rho\pi$ puzzle, it applies to other decay modes as well, such as the pseudoscalar-pseudoscalar mode like $K^0_SK^0_L$. Recently, the BES Collaboration reported the branching fractions of the $K^0_SK^0_L$ final state in J/ψ and ψ' decays [9,10]:

$$\mathcal{B}(J/\psi \to K^0_SK^0_L) = (1.82 \pm 0.04 \pm 0.13) \times 10^{-4},$$
$$\mathcal{B}(\psi' \to K^0_SK^0_L) = (5.24 \pm 0.47 \pm 0.48) \times 10^{-5}.$$

These results yield $Q_{K^0_SK^0_L} = (28.8 \pm 3.7)\%$, which is enhanced relative to the 12% rule by more than 4σ.

By assuming that the pQCD 12% rule holds for the $K^0_SK^0_L$ mode between J/ψ and $\psi(2^3S_1)$, in the S- and D-wave charmonia mixing scheme, Ref. [11] predicts the decay rate of $\psi'' \to K^0_SK^0_L$ in a range, that is

$$0.12 \pm 0.07 \le 10^5 \times \mathcal{B}(\psi'' \to K^0_SK^0_L) \le 3.8 \pm 1.1.$$

Here the upper bound corresponds to $\phi = 0°$ and the lower bound to $\phi = 180°$, where ϕ is the relative phase between $\langle K^0_SK^0_L \mid 1^3D_1\rangle$ and $\langle K^0_SK^0_L \mid 2^3S_1\rangle$. The uncertainties are due to the mixing angle θ between $\psi(2^3S_1)$ and $\psi(1^3D_1)$ states, and the measurements of $\mathcal{B}(\psi' \to K^0_SK^0_L)$ and $\mathcal{B}(J/\psi \to K^0_SK^0_L)$.

In this paper, we report a search for $\psi'' \to K^0_SK^0_L$ at BESII.

II. THE EXPERIMENT

The data used for the analysis are taken with the BESII detector at the BEPC storage ring in the vicinity of the ψ'' peak (± 4 MeV around ψ'' nominal mass). The data sample corresponds to a total of $17.7(1 \pm 5\%)$ pb^{-1} luminosity as determined from large angle Bhabha events [12].

The BES is a conventional solenoidal magnet detector that is described in detail in Ref. [13]; BESII is the upgraded version of the BES detector [14]. A 12-layer vertex chamber (VC) surrounding the beam pipe provides trigger information. A 40-layer main drift chamber (MDC), located radially outside the VC, provides trajectory and energy loss (dE/dx) information for charged tracks over 85% of the total solid angle. The momentum resolution is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks is $\sim$8%. An array of 48 scintillation counters surrounding the MDC measures the time of flight (TOF) of charged tracks with a resolution of $\sim$200 ps for hadrons. Radially outside the TOF system is a 12 radiation length, lead-gas barrel shower counter (BSC). This measures the energies of electrons and photons over $\sim$80% of the total solid angle with an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV). Outside of the solenoidal coil, which provides a 0.4 T magnetic field over the tracking volume, is an iron flux return that is instrumented with three double layers of counters that identify muons of momentum greater than 0.5 GeV/c.

III. MONTE CARLO

Monte Carlo (MC) is used for mass resolution and detection efficiency determination, as well as the background study.

For the signal channel, $\psi'' \to K^0_SK^0_L$, the angular distribution of K^0_S or K^0_L is generated as $\sin^2\theta$, where θ is the polar angle in laboratory system. K^0_L is allowed to decay according to its lifetime in the detector and only $K^0_S \to \pi^+\pi^-$ is generated. For this study, 10 000 events are generated.

One of the main backgrounds is from $e^+e^- \to \gamma\gamma(\gamma)$ events, with one photon converted into the e^+e^- pair in the detector material. This is studied with a MC sample which is 4 times as large as in the real data.

Another background channel is $K^{*0}(892)\overline{K}^0 + \text{c.c.}$ from ψ'' decays or e^+e^- direct production. Ten thousand events are generated for studying this background, which is about 100 times more than in the real data.

$2M$ $D\bar{D}$ pairs are generated for studying the background channels with c-quark production. This sample is about 14 times more than the real data sample.

The continuum channels from u, d, and s quark fragmentation are generated with JETSET7.4 [15]; the MC sample is about 4 times as large as in the real data.

The simulation of the detector response is a GEANT3 based package, where the interactions of the secondary particles with the detector material are simulated. Reasonable agreement between data and Monte Carlo simulation has been observed in various testing channels including $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $J/\psi \to p\overline{p}$, and $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$).

IV. EVENT SELECTION

The event selection criteria are all used in the analyses of the same final states at J/ψ [9] and ψ' energy [10]. They are listed here for an easy reference.

(1) The number of charged tracks is required to be two with net charge zero. Each track should have good helix fit so that the error matrix of the track fitting is available for secondary vertex finding. The track is required to be within $|\cos\theta| < 0.80$, where θ is the polar angle of the track in MDC in the laboratory system.

(2) The two tracks are assumed to be π^+ and π^-, to find the intersect of the two tracks near the interaction point, which will be taken as the secondary vertex. The $\pi^+\pi^-$ mass is required to be within 2σ of the MC predicted mass resolution (8.9 MeV/c). The decay length in the xy plane, $L_{xy} > 0.01$ m, is required.

(3) The sum of the total energy of the photon candidates $E_\gamma^{\rm tot} < 1.0$ GeV is used to remove the $e^+e^- \to \gamma\gamma(\gamma)$ backgrounds, with one photon converted into e^+e^- pairs in the detector material. A neutral cluster is considered to be a photon candidate when the angle between the nearest charged track and the cluster in the xy plane is greater than 15°. The first hit is in the beginning six radiation lengths, and the angle between the cluster development direction in the BSC and the photon emission direction in the xy plane is less than 37°.

The above selection criteria are exactly the same as used for the $\psi' \to K_S^0 K_L^0$ analysis [10]. To be unbiased with the expected small signal in the analysis, we try to fix the event selection criteria before looking at real data. By looking at the K_S^0 momentum distributions of the background MC samples generated, it is found that the background from the $e^+e^- \to \gamma\gamma(\gamma)$ and $K^{*0}(892)\overline{K}^0$ + c.c. is still very large. Then the selection criteria used for the $J/\psi \to K_S^0 K_L^0$ selection [9] are further applied to reduce the background level.

(4) The total BSC energy associated with the two charged tracks less than 1.0 GeV or the total XSE (the difference from the expected dE/dx for the electron hypothesis divided by the dE/dx resolution) is less than −4.

(5) The opening angle between the two charged tracks is larger than 20°.

(6) $E_\gamma^{lft} < 0.1$ GeV, where E_γ^{lft} is the sum of the energies of the photon candidates outside a cone around the direction of K_L^0 ($\cos\theta < 0.95$).

Cuts 4 and 5 are used to reduce the gamma conversion background and cut 6 is used to reduce the $K^{*0}(892)\overline{K}^0$ + c.c. background. After all the above cuts, there are no events left in the $e^+e^- \to \gamma\gamma(\gamma)$ MC sample, and the remaining $K^{*0}(892)\overline{K}^0$ + c.c. event in the signal region is less than 1 after normalized to the $K^{*0}(892)\overline{K}^0$ + c.c. cross section [16] and the luminosity of the data sample.

The signal region is defined as the K_S^0 momentum to be larger than 1.737 GeV/c, which is 2σ ($\sigma = 42$ MeV/c) lower than the MC predicted K_S^0 momentum for the signal channel.

After requiring all the above criteria, the K_S^0 momentum distribution of real data is shown in Fig. 1 as the black dots with error bars; the distribution of the events in the K_S^0 mass sidebands is also shown (shaded histogram). We can see that there is no clear difference between events in the K_S^0 mass region and those in the K_S^0 mass sidebands. In the same plot, we also give the MC predicted position of the signal events (blank histogram). It can be seen that there is no clear signal in data at the signal region. So we conclude that there is no $K_S^0 K_L^0$ signal observed, and the upper limit of the $\psi'' \to K_S^0 K_L^0$ branching fraction will be determined based on the two candidates in the signal region.

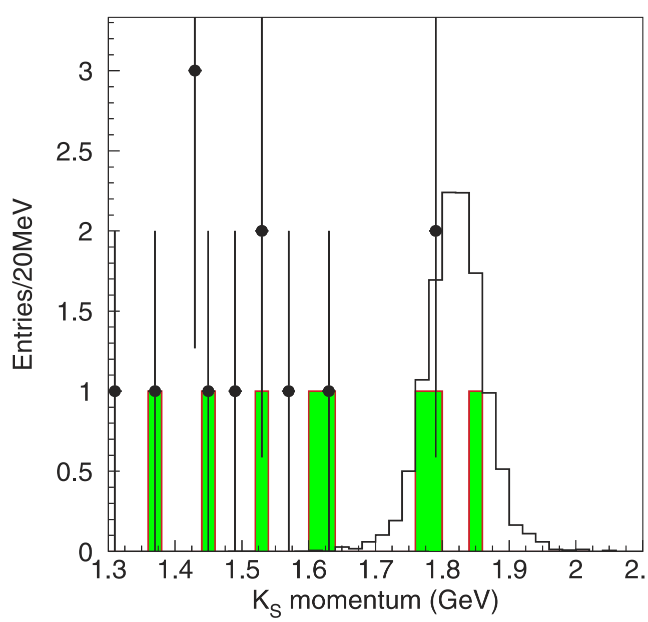

FIG. 1 (color online). The K_S^0 momentum distribution. Data are shown by dots with error bars; the K_S^0 mass sidebands background is shown by the shaded histogram. The blank histogram is the MC simulated signal channel events, not normalized.

V. EFFICIENCIES AND SYSTEMATIC ERRORS

The detection efficiency of the signal is estimated with 10 000 Monte Carlo simulated events, and one gets $\varepsilon_{MC} = (41.44 \pm 0.49)\%$, where the error is due to the statistics of the Monte Carlo sample. The trigger efficiency of $K_S^0 K_L^0$ events, which is lower because of the K_S^0 decays, is measured to be $(76.0 \pm 1.8)\%$ [10]. It is found that the reconstruction efficiency of the K_S^0 in Monte Carlo is a bit higher than that in data [9], a correction factor of $(96.3 \pm 3.3)\%$ should be applied to the Monte Carlo simulation. After taking into account all these factors, the global efficiency is $\varepsilon = 30.33\%$.

The systematic error for the branching fraction measurement comes from the efficiencies of the photon identification, the secondary vertex finding, MDC tracking, the trigger, the branching fraction used, the number of ψ'' events, the K_S^0 mass cut, angular distributions, and so on. All these have been studied extensively in the analyses of J/ψ and $\psi' \to K_S^0 K_L^0$ [9,10], and they are borrowed from the two analyses directly.

Table I lists the systematic error from all sources. The uncertainties of the $\mathcal{B}(\psi'' \to e^+ e^-)$ and luminosity will affect the determination of the total number of the ψ'' events; the former comes from the PDG [17] while the latter is from the measurement used in Ref. [12].

Adding the errors from all the sources in quadrature, the total systematic error is 17%.

VI. RESULTS AND DISCUSSION

The upper limit of the branching fraction of $\psi'' \to K_S^0 K_L^0$ calculated with

$$\mathcal{B}(\psi'' \to K_S^0 K_L^0) < \frac{n_{UL}^{obs}/\varepsilon}{N_{\psi''}\mathcal{B}(K_S^0 \to \pi^+\pi^-)(1-\sigma^{sys})},$$

where n_{UL}^{obs} is the upper limit of the observed number of events, which is 5.32 for two observed events at 90% C.L. assuming there is no background. ε is the global efficiency for the signal channel. $N_{\psi''}$ is the number of ψ'' events, calculated with the total luminosity and the resonance parameters listed by PDG [17]. The systematic error of the measurement is considered by introducing $1 - \sigma^{sys}$ in the denominator of the formula for branching fraction calculation.

TABLE I. Summary of the systematic errors.

Source	Systematic errors (%)
MC statistics	1.3
E_γ^{tot}	2.0
E_γ^{lft}	1.3
2nd vertex finding	3.4
MDC tracking	4.0
Trigger efficiency	2.4
$\mathcal{B}(\psi'' \to e^+e^-)$	15.0
Luminosity	5.0
$\mathcal{B}(K_S^0 \to \pi^+\pi^-)$	0.4
Total σ^{sys}	17.0

TABLE II. Numbers used in the calculation of the upper limit of the branching fraction.

Quantity	Value
n_{UL}^{obs}	5.32
ε	30.33%
$N_{\psi''}$	1.45×10^5
$\mathcal{B}(K_S^0 \to \pi^+\pi^-)$	0.6860
σ^{sys}	17%
$\mathcal{B}(\psi'' \to K_S^0 K_L^0)$	$<2.1 \times 10^{-4}$

Using the numbers from above (listed in Table II), one gets, at 90% C.L.,

$$\mathcal{B}(\psi'' \to K_S^0 K_L^0) < 2.1 \times 10^{-4}.$$

Comparing to the corresponding theoretical calculation of the branching fraction based on the S- and D-wave mixing model and the 12% rule, the current upper limit is still well above the upper bound of the prediction [11] of 3.8×10^{-5}. To further pin down the upper limit of the branching fraction, thus to check the validity of "Rosner's assumption" and the solution of the $K_S^0 K_L^0$ enhancement puzzle observed in ψ' and J/ψ decays, a larger data sample is needed. The existing 55 pb^{-1} ψ'' data and the planned 3 fb^{-1} ψ'' data samples from CLEOc [8] will be obviously helpful for this study.

VII. SUMMARY

The flavor SU(3) breaking process $K_S^0 K_L^0$ is searched for in ψ'' decays with the BESII data sample at ψ'' energy, and the upper limit of the branching fraction is determined to be $\mathcal{B}(\psi'' \to K_S^0 K_L^0) < 2.1 \times 10^{-4}$. The upper limit is still above the upper bound of the prediction [11].

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