First measurement of the branching fraction of the decay $\psi(2S)\rightarrow\tau^+\tau^-$

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The branching fraction of the $\psi(2S)$ decay into $\tau^+\tau^-$ has been measured for the first time using the BES detector at the Beijing Electron-Positron Collider. The result is $B_{\tau\tau}=(2.71\pm0.43\pm0.55)\times10^{-3}$, where the first error is statistical and the second is systematic. This value, along with those for the branching fractions into e^+e^- and $\mu^+\mu^-$ of this resonance, satisfy well the relation predicted by the sequential lepton hypothesis. Combining all these values with the leptonic width of the resonance, the total width of the $\psi(2S)$ is determined to be (252 ± 37) keV.

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I. INTRODUCTION

The $\psi(2S)$ provides a unique opportunity to compare the three lepton generations by studying the leptonic decays $\psi(2S)\to e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$. The sequential lepton hypothesis leads to a relationship between the branching fractions of these decays, B_{ee}, $B_{\mu\mu}$, and $B_{\tau\tau}$ given by

$$\frac{B_{ee}}{v_e(\frac{3}{2}-\frac{1}{2}v_e^2)}=\frac{B_{\mu\mu}}{v_\mu(\frac{3}{2}-\frac{1}{2}v_\mu^2)}=\frac{B_{\tau\tau}}{v_\tau(\frac{3}{2}-\frac{1}{2}v_\tau^2)} \tag{1}$$

with $v_l=[1-(4m_l^2/M_{\psi(2S)}^2)]^{1/2}$, $l=e$, μ, τ. Substituting mass values for the leptons and the $\psi(2S)$ gives

$$B_{ee}\simeq B_{\mu\mu}\simeq\frac{B_{\tau\tau}}{0.3885}\equiv B_{ll}\,. \tag{2}$$

Previous experiments have provided measurements of B_{ee} and $B_{\mu\mu}$ for the $\psi(2S)$ [1,2]. We present here the first measurement of $B_{\tau\tau}$ for the $\psi(2S)$ and compare it to the existing measurements of B_{ee} and $B_{\mu\mu}$ for this resonance. Combining these values with previous results for the leptonic width of this resonance [3,4], we determine the total width of the $\psi(2S)$.

II. BES DETECTOR AND DATA SAMPLE

The data were taken with the Beijing Spectrometer (BES) at the Beijing Electron-Positron Collider (BEPC). BES, a general-purpose magnetic detector, has been described in detail elsewhere [5]. Briefly, a central drift chamber surrounding the beam pipe is used for trigger purposes. The main drift-chamber system measures the momentum of charged tracks over 85% of the 4π solid angle with a resolution of $\sigma_p/p=1.7\%\sqrt{1+p^2}$ (p in GeV/c). Complementary measurements of specific ionization (dE/dx) and time of flight are used for particle identification. The dE/dx resolution for minimum ionizing particles is 9%. Scintillation counters measure the time of flight of charged particles over 76% of 4π with a resolution of 330 ps for Bhabha events and 450 ps for hadrons. A cylindrical 12-radiation-length Pb/gas electromagnetic calorimeter operating in self-quenching streamer mode and covering 80% of 4π provides an energy resolution of $\sigma_E/E=22\%/\sqrt{E}$ (E in GeV) and spatial resolutions of $\sigma_\phi=7.9$ mrad, and $\sigma_z=3.6$ cm. Endcap time-of-flight counters and shower counters are not used in this analysis. A conventional solenoid encloses the calorimeter, providing a 0.4 T field. The outermost component is a three-layer iron flux return instrumented for muon identification which yields spatial resolutions of $\sigma_z=5$ cm and $\sigma_{r\phi}=3$ cm over 68% of 4π for muons with momenta greater than 550 MeV/c.

This analysis is based on a total integrated luminosity of about 6.1 pb^{-1} at a center-of-mass energy corresponding to the $\psi(2S)$ resonance, $\sqrt{s}=3686.36$ MeV, with an uncertainty of 0.29 MeV. The spread in the center-of-mass energy of the collider is $\Delta=(1.4\pm0.1)$ MeV. The data, a total of 3.96 million $\psi(2S)$ events, were collected in two separate running periods. Because of the difference in running conditions of the detector in the two periods, the two distinct data sets, I and II, are analyzed separately.

III. EVENT SELECTION

The $\tau^+\tau^-$ events are identified by requiring that one τ decays via $e\nu\bar{\nu}$ and the other via $\mu\nu\bar{\nu}$. To select candidate $\tau^+\tau^-$ events, it is first required that exactly two oppositely charged tracks be well reconstructed. For each track, the point of closest approach to the beam line must have $|r|<1.5$ cm, and $|z|<15$ cm, where z is measured along the beam line from the nominal beam crossing point. The acolinearity angle, $\theta_{\rm acol}$, defined as the angle between the outgoing charged tracks, is required to satisfy $10°\leqslant\theta_{\rm acol}\leqslant170°$ to reject Bhabhas, muon pairs, and cosmic rays. The acoplanarity angle, $\theta_{\rm acop}$, defined as the angle between the planes defined by the beam direction and the momentum vector of each charged track, is required to satisfy $\theta_{\rm acop}\geqslant20°$ to suppress radiative Bhabhas and radiative muon pairs. Furthermore, each track is required to satisfy $|\cos\theta|\leqslant0.65$, where θ is the polar angle, to ensure that it is contained within the fiducial region of the barrel electromagnetic calorimeter.

Next, it is required that the transverse momentum of each charged track be above the 70 MeV/c minimum needed to traverse the barrel time-of-flight (TOF) counter and reach the outer radius of the calorimeter in the 0.4 Tesla magnetic field. In addition, the momentum must be less than the maximum kinematically allowed value for a τ decay at the c.m. energy of the $\psi(2S)$ within a tolerance of 3 standard deviations in momentum resolution.

The search for $\tau^+\tau^-$ production events is restricted to final states which do not contain π^0's or γ's. Consequently, there should be no isolated photon present in the calorimeter, which is defined as an electromagnetic shower having energy greater than 60 MeV and a separation from the nearest charged track of at least 12°.

A particle identification procedure is applied to the selected events. Using the information provided by the main drift chamber (dE/dx), the scintillation counters (time of flight), the electromagnetic calorimeter (shower energy), we define *Xse* as the dE/dx separation, *Tse* as the TOF separation, and *Sse* as the shower energy separation, all assuming the electron hypothesis. Here, separation means {(measured value−expected value)/resolution}. Then, to identify a track as a electron we require $-4\leqslant Tse\leqslant0.5$, $-1\leqslant Xse\leqslant2$, $-4\leqslant Sse\leqslant4$ if its momentum is less than 0.35 GeV/c; $-4\leqslant Tse\leqslant1.5$, $-2\leqslant Xse\leqslant2$, $-1.5\leqslant Sse\leqslant4$ if its momentum is between 0.35 GeV/c and 0.7 GeV/c; or $-4\leqslant Tse\leqslant4$, $-1.5\leqslant Xse\leqslant2$, $-2\leqslant Sse\leqslant4$ if its momentum is greater than 0.7 GeV/c. A track is assigned as a muon if there are at least two hits in the muon counters. Figures 1 and 2 show distributions of the sum of the lepton energies and the acoplanarity angle for data and Monte Carlo events passing the selection criteria. The numbers of events selected for the first, second, and combined data sets are 77, 140, and 217, respectively, as shown in Table I.

The same requirements are applied to 5 million events from a control sample taken at the J/ψ energy to estimate the expected contributions of backgrounds n_{bg} to be subtracted

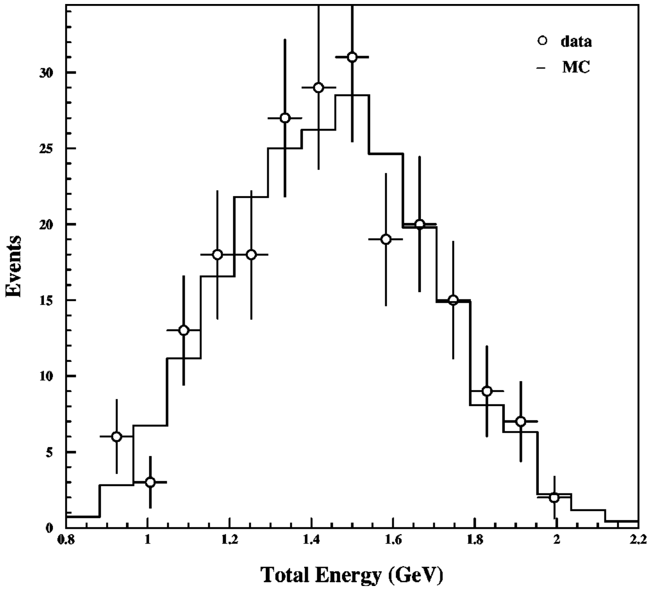

FIG. 1. The distributions of the sum of the lepton energies for data and Monte Carlo events passing the selection criteria.

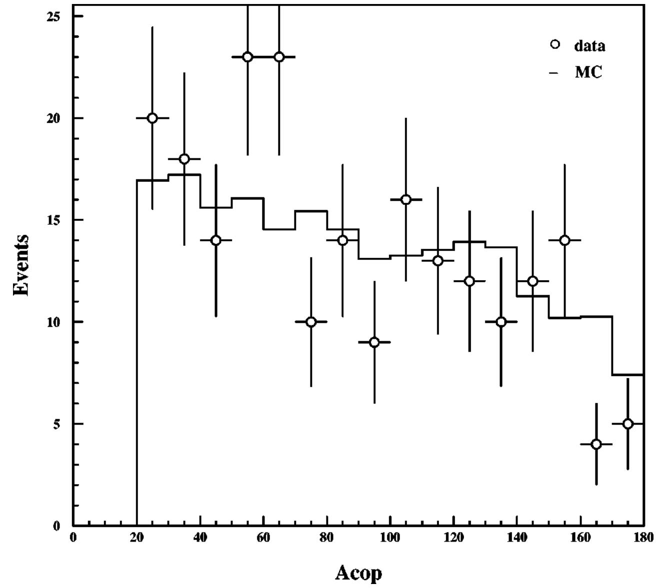

FIG. 2. The distributions of the acoplanarity angle for data and Monte Carlo events passing the selection criteria.

from the selected $e\mu$ events $n_{e\mu}$. Only one event meets the criteria for the $e\mu$ topology, which corresponds to a background of 0.27 events for data set I and 0.49 events for data set II. Because of possible small systematic differences between the J/ψ and $\psi(2S)$ samples, we also applied our selection criteria to a 4 million event $\psi(2S)$ Monte Carlo sample with $\tau\tau$ production turned off [6]. No events passed our selection criteria. A Monte Carlo study on the two-photon process has also been performed; its contamination is estimated to be negligible.

IV. DATA ANALYSIS AND RESULTS

To obtain the number of resonant τ-pair events, the QED contribution including the interference effect is subtracted from the total number of $\tau^+\tau^-$ events. $B(\tau\tau)$ is calculated from

$$B(\tau\tau)=\frac{(n_{e\mu}-n_{bg})/(B\epsilon_{\mathrm{trig}}\epsilon_d)-\sigma_{Q+I}\mathcal{L}}{N_{\psi(2S)}}. \qquad (3)$$

Here B is the fraction of $\tau^+\tau^-$ events yielding the $e\mu$ topology, which is equal to 0.06194 [7]; ϵ_{trig} is the trigger efficiency, which for $e\mu$ events within fiducial volume is estimated to be approximately 100%; ϵ_d is the detection efficiency, which is determined by using 4×10^5 Monte Carlo–simulated events that are generated by KORALB [8]. The results are $\epsilon_d=14.49\%$ for data set I and 14.39% for data set II (the luminosity-weighted average of ϵ_d for the whole data is 14.42%). σ_{Q+I} is the QED τ-pair production cross section including interference; $N_{\psi(2S)}$ is the number of produced $\psi(2S)$ events; and $\mathcal{L}$ is the accumulated luminosity at the resonance.

Including the c.m. energy spread Δ, the initial state radiation correction [9] $F(x,W)$, and the vacuum polarization corrections [10] $\Pi(W)$, the total τ-pair production cross section near $\psi(2S)$ threshold is [11]

$$\sigma(W)=\frac{1}{\sqrt{2\pi}\Delta}\int_0^\infty dW' e^{-(W-W')^2/2\Delta^2} \times\int_0^{1-(2m_\tau/W')^2} dxF(x,W')\sigma_1(W'\sqrt{1-x}) \qquad (4)$$

where σ_1 is given by

$$\sigma_1(W)=\frac{4\pi\alpha^2}{3W^2}\,\frac{\beta(3-\beta^2)}{2}\,\frac{F_c(\beta)F_r(\beta)}{[1-\Pi(W)]^2} \times\left\{1+\frac{3M^3}{\alpha_s}\Gamma_{ee}^2\frac{1}{1+\frac{2m_e^2}{M^2}}\frac{1}{\left(1-\frac{4m_e^2}{M^2}\right)^{1/2}}\right. \times\frac{2(W^2-M^2)}{(W^2-M^2)^2+M^2\Gamma^2}$$

TABLE I. Numbers used to calculate $B_{\tau\tau}$. The first error is statistical and the second is systematic.

Data set	$n_{e\mu}$	n_{bg}	ϵ_d	$\mathcal{L}$ (pb^{-1})	$N_{\pi\pi J/\psi}(10^6)$	$N_{\psi(2S)}(10^6)$
I	77	0.27	0.1449	$2.123\pm0.015\pm0.051$	$0.4293\pm0.0017\pm0.0076$	$1.385\pm0.005\pm0.127$
II	140	0.49	0.1439	$3.929\pm0.019\pm0.098$	$0.7980\pm0.0023\pm0.0092$	$2.574\pm0.007\pm0.234$
Total	217	0.76	0.1442	$6.052\pm0.024\pm0.149$	$1.227\pm0.003\pm0.017$	$3.959\pm0.009\pm0.362$

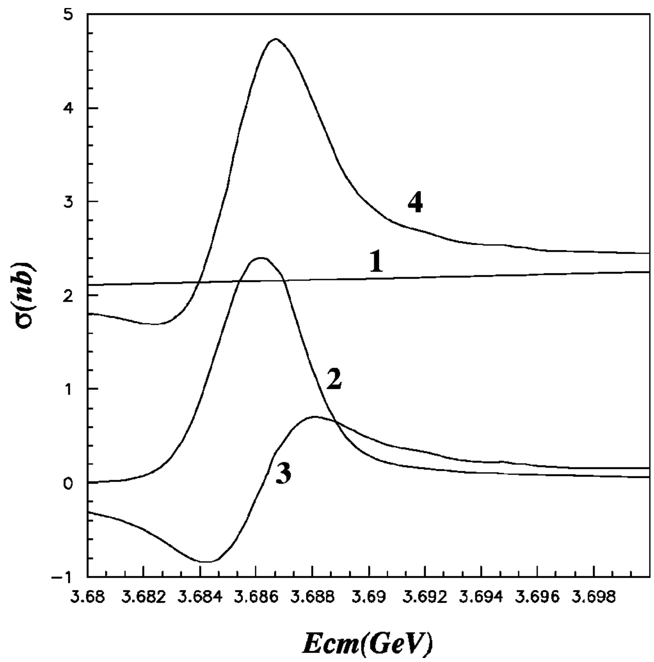

FIG. 3. The production cross section of $e^+e^- \rightarrow \pi^+\pi^-$ [1 indicates the QED process, 2 indicates $\psi(2S)$ production, 3 indicates interference, and 4 indicates the total].

$$+\left(\frac{3M^3}{\alpha_s}\right)^2 \Gamma_{ee}^2 \frac{1}{\left(1+\frac{2m_e^2}{M^2}\right)^{1/2}} \frac{1}{1-\frac{4m_e^2}{M^2}} \times \frac{1}{(W^2-M^2)^2+M^2\Gamma^2}\Bigg\}$$

$$=\sigma_1^{\mathrm{QED}}+\sigma_1^{\mathrm{int}}+\sigma_1^{\psi(2S)}. \tag{5}$$

W is the c.m. energy, M is the mass of $\psi(2S)$, and $\beta = \sqrt{1-(2m_\tau/W)^2}$. The Coulomb interaction and final state radiation corrections are described by the functions $F_c(\beta)$ and $F_r(\beta)$ [12].

The total cross section, which includes QED production, $\psi(2S)$ resonance production, and interference, is shown in Fig. 3. For this experiment, $W = 3686.36$ MeV and $\Delta = 1.4$ MeV, and we get $\sigma_{Q+I} = 2.230$ nb.

The number of produced $\psi(2S)$ event $N_{\psi(2S)}$ is determined from a study of inclusive J/ψ produced in $\psi(2S)$ decays in the topology $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ [13]. To estimate $N_{\psi(2S)}$, the Particle Data Group (PDG) value for $B(\psi(2S) \rightarrow \pi^+\pi^- J/\psi) = (31.0 \pm 2.8)\%$ [7] is used.

The luminosity $\mathcal{L}$ is determined by using wide-angle Bhabha events at the $\psi(2S)$ in the BES detector and is given by

$$\mathcal{L} = \frac{N_{\mathrm{QED}}}{\sigma_{\mathrm{QED}} \epsilon_t \epsilon_d}, \tag{6}$$

where N_{QED}, σ_{QED}, ϵ_t, and ϵ_d refer, respectively, to the observed number of Bhabha events at the $\psi(2S)$, the Bhabha cross section corrected for interference at the resonance, the trigger efficiency, and the detection efficiency for Bhabha events. In order to obtain pure Bhabha events, the e^+e^- events from $\psi(2S) \rightarrow e^+e^-$ as well as from $\psi(2S) \rightarrow$ neutral $J/\psi, J/\psi \rightarrow e^+e^-$, should be subtracted from the total number of events. These events are symmetric in $\cos\theta$ while the Bhabha events are asymmetric in $\cos\theta$. Using the $\cos\theta$ distribution for e^+e^- production relative to $\cos\theta = 0$, a relation for the number of Bhabha events can be obtained

$$N_{\mathrm{QED}} = \frac{A_1 - A_2}{1 - 2\alpha}, \tag{7}$$

where A_1 and A_2 are the total number of e^+e^- events found for $\cos\theta < 0$ and $\cos\theta > 0$, respectively, and α is the fraction of Bhabha events with $\cos\theta < 0$, which is determined by a Monte Carlo simulation.

TABLE II. Branching fraction $B_{\tau\tau}/B_{\pi^+\pi^- J/\psi}$ and final branching ratio $B_{\tau\tau}$.

Data set	$B_{\tau\tau}/B_{\pi^+\pi^- J/\psi}(10^{-3})$	$B_{\tau\tau}(10^{-3})$
I	$8.89 \pm 2.35 \pm 1.61$	$2.76 \pm 0.73 \pm 0.56$
II	$8.63 \pm 1.72 \pm 1.63$	$2.68 \pm 0.53 \pm 0.56$
Total	$8.73 \pm 1.39 \pm 1.57$	$2.71 \pm 0.43 \pm 0.55$

The results of this measurement are summarized in Tables I and II. Combining the results from the two different running periods, the branching fraction of the $\psi(2S)$ decaying into $\tau^+\tau^-$ is calculated to be

$$B_{\tau\tau} = (2.71 \pm 0.43 \pm 0.55) \times 10^{-3}, \tag{8}$$

where the first error is statistical and the second is systematic. The overall relative systematic error of 20.2% includes contributions from the luminosity $\mathcal{L}$ (3.1%); the number of $\psi(2S)$ events, $N_{\psi(2S)}$ (9.1%); the selection criteria for $e\mu$ topology (11.3%); and the calculated value of σ_{QED} due to uncertainties in the c.m. energy scale and the spread in c.m. energy (10.8%). The luminosity systematic error is determined from the cross section uncertainty and from the changes found when varying the selection criteria.

V. CONCLUSION

In Table III we summarize the existing measurements of the leptonic decays of the $\psi(2S)$. Our value of $B_{\tau\tau}$, corrected by a factor of 0.3885, as indicated in Eq. (2), agrees with the values of B_{ee} and $B_{\mu\mu}$ [7]. Assuming lepton universality, the average value B_{ll} is determined to be $(8.4 \pm 1.0) \times 10^{-3}$. The leptonic width ($\Gamma_{ee}$) of the $\psi(2S)$ has been determined to be (2.12 ± 0.18) keV [7]. From the relationship $\Gamma_{\mathrm{tot}} = \Gamma_{ee}/B_{ll}$ we find $\Gamma_{\mathrm{tot}} = (252 \pm 37)$ keV, which is

TABLE III. Leptonic branching fractions of the $\psi(2S)$ in 10^{-3}.

B_{ee}	$B_{\mu\mu}$	$B_{\tau\tau}/0.3885$
8.8 ± 1.3 [7]	10.3 ± 3.5 [7]	$7.0 \pm 1.1 \pm 1.4$

consistent with the direct measurement value (306 $\pm$39) keV by the E760 Collaboration [14] within about one standard deviation.

In conclusion, we have measured $B_{\tau\tau}$ for the $\psi(2S)$. This result, along with the previous data of B_{ee} and $B_{\mu\mu}$, satisfy well the relation predicted by the sequential lepton hypothesis. Combining these values we have calculated the total width for this resonance.

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