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 $B_{\tau\tau} = (3.2 \pm 0.6 \pm 0.6) \times 10^{-3}$, where the first error is statistical and the second is systematic. This value, along with the previous measurements of the branching fractions into e^+e^- and $\mu^+\mu^-$, well satisfy the relation predicted by the hypothesis of $e-\mu-\tau$ universality. Combining all these values with the leptonic width of the resonance, the total width of the $\psi(2S)$ is found to be (256±38) keV.

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In the $c\bar{c}$ system the $\psi(2S)$ provides an unique opportunity to compare the three lepton generations by studying the leptonic decays $\psi(2S) \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$. It is easy to show within the context of the sequential lepton hypothesis that the relations between the branching fractions of these decays, B_{ee}, $B_{\mu\mu}$, and $B_{\tau\tau}$ are 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 $v_l = (1-\frac{4m_l^2}{M^2})^{\frac{1}{2}}$, $l = e, \mu, \tau$; or

$$B_{ee} \simeq B_{\mu\mu} \simeq \frac{B_{\tau\tau}}{0.3885} \tag{2}$$

by substituting the values of m_e, m_μ, m_τ, and M, the masses for electron, muon, tau lepton, and $\psi(2S)$, respectively. Previous experiments have yielded measurements of B_{ee} and $B_{\mu\mu}$ for the $\psi(2S)$ [1][2], but no data for $B_{\tau\tau}$. 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 the previous result of the leptonic width of this resonance [3], we determine the total width of the $\psi(2S)$.

The data were taken with the Beijing Spectrometer (BES) at the Beijing Electron–Positron Collider (BEPC). The BES, a general–purpose magnetic detector, has been described in detail elsewhere [4]. We limit ourselves here to a brief description of the relevant features. An inner drift chamber surrounding the beam pipe is used for trigger purposes. The main drift-chamber system, in a 0.4 Tesla magnetic field, measures the momentum of charged tracks over 85% of the 4π solid angle with a resolution of $\sigma_p/p = 0.02\sqrt{1+p^2}$ (p in GeV/c). Measurements of dE/dx with resolution 8.5% allow particle identification. Scintillation counters measure the time-of-flight of charged particles over 76% of 4π with a Bhabha resolution of 370 ps. A cylindrical twelve-radiation-length Pb/gas electromagnetic calorimeter operating in limited streamer mode covering 80% of 4π achieves energy resolution $\sigma_E/E = 0.25/\sqrt{E}$ (E in GeV) and spatial resolution $\sigma_\phi = 4.5$ mrad, $\sigma_z = 2$ cm. Endcap time-of-flight counters and shower counters are not used in this analysis. The outermost component is a three-layer iron flux return instrumented for muon identification yields spatial resolutions $\sigma_z = 5$ cm, $\sigma_{r\phi} = 3$ cm over 68% of 4π for muons with momentum greater than 550 MeV/c.

This analysis is based on an accumulated luminosity of about 2 pb^{-1} at a center-of-mass energy corresponding to the $\psi(2S)$ resonance, $\sqrt{s} = (3.686 \pm 0.29)$ MeV. The spread in the center-of-mass energy of the collider is $\Delta = (1.4 \pm 0.1)$ MeV.

The $\tau^+\tau^-$ events are identified by means of four topologies, $e\mu$, eh, ee, and μh, where h denotes a charged π or K (as an example, the event in which one τ decays via $e\nu\overline{\nu}$ and the other via $\mu\nu\overline{\nu}$ is referred to as an $e\mu$ topology). To select candidate $\tau^+\tau^-$ events, it is first required that exactly two oppositely charged tracks are well reconstructed with net charge zero. For each track, the point of closest approach to the beam line must have $|x| < 1.5$ cm, $|y| < 1.5$ cm, and $|z| < 15$ cm, where z is measured along the beam line from the nominal beam crossing point; in addition $|z_1 - z_2|$ must be less than 5 cm. Defining the acolinearity angle, θ_{acol}, as the angle between the momentum vectors of the two final state charged tracks, a requirement on this angle, $10° \leq \theta_{acol} \leq 170°$, is applied. Defining the acoplanarity angle, θ_{acop}, as the angle between the planes spanned by the beam direction and the momentum vectors of the two final state charged tracks, $\theta_{acop} \geq 10°$ for $e\mu$, $\geq 20°$ for ee and μh, and $\geq 25°$ for eh are required. Furthermore, each track is required to satisfy $|\cos\theta| \leq 0.75$, where θ is the polar angle, to ensure that it is contained within the barrel region of the detector.

Next, it is required that the transverse momentum of each charged track be above the 100 MeV/c minimum needed to traverse the barrel time-of-flight counter and reach the outer radius of the calorimeter in the 0.4 Tesla magnetic field. In addition, the magnitude of the momentum must be less than the maximum expected in any τ decay at the given c.m. energy 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 by requiring that it have energy > 60 MeV and be separated from the nearest charged track by $> 12°$.

The particle identification procedure is applied to the selected events. By making use of the additional information provided by the drift chamber gas (dE/dx), the scintillation counters (time-of-flight), the electromagnetic calorimeter (shower energy and hit number), as well as the muon counters (μ-hit status), a track is assigned either the electron, muon, pion, or hadron (i.e.,π or K) identity.

Finally, the $\tau^+\tau^-$ final states are separated from the QED background by cutting on the variable $PTEM$, which is defined as

$$PTEM = \frac{P_T}{E_{miss}^{max}} = \frac{(\vec{P_1} + \vec{P_2})_T}{W - |\vec{P_1}| - |\vec{P_2}|} \tag{3}$$

(i.e. the ratio of the net observed transverse momentum to the maximum possible value of the missing energy), at small values. The relevant $PTEM$ criteria are : ≥ 0.1 for $e\mu$ events; ≥ 0.25 for eh or ee events; and ≥ 0.35 for μh events.

The same requirements are applied to 5 million events from a data sample taken at the J/ψ energy to estimate the expected contributions of backgrounds to be subtracted from the selected events, they are 1.1, 1.6, 0.3, and 0 events for $e\mu$, eh, ee, and μh topologies, respectively. Monte Carlo study on the two–photon process has also been performed, its comtamination is estimated to be negligible.

In order to translate observed events after background subtraction n in each topology into produced $\tau^+\tau^-$ events $N_{\tau\tau}$, it is necessary to make substantial corrections to account for the fraction of $\tau^+\tau^-$ events yielding the relevant topology B, the trigger efficiency ϵ_{trig}, and efficiency for detecting corresponding events ϵ_d by using

$$N_{\tau\tau} = n/B\epsilon_d\epsilon_{trig}. \tag{4}$$

However, a direct calculation of ε_d using a Monte Carlo simulation of the BES detector could lead to a large systematic uncertainty that is hard to estimate properly. To get rid of such an uncertainty as far as possible, an alternative approach is used here. First, we determine the detection efficiency $\sqrt{s} = 4.03 GeV$ for events in a given topology, $\varepsilon_d^{'}$, by making use of the data collected by the BES for studies of the Ds physics. The value of $\varepsilon_d^{'}$, obtained with use of this continuum data, is just the ratio of observed events to the corresponding number of events expected from QED over the 4π solid angle, $\varepsilon_d^{'} = n^{'}/B\epsilon_{trig}^{'}\sigma_{QED}^{'}\mathcal{L}^{'}$, where $n^{'}$, $\epsilon_{trig}^{'}$, $\sigma_{QED}^{'}$, and $\mathcal{L}^{'}$ refer respectively to the number of observed events, the trigger efficiency, the QED τ-pair cross section, and the accumulated luminosity used for this measurement [5] at 4.03 GeV. The background comtamination in $n^{'}$ due to processes such as $D^+ \rightarrow \bar{K}^0 l^+ \nu_l$, l=e or μ, is estimated to be negligible according to Monte Carlo simulation. We then relate $\varepsilon_d^{'}$ to ε_d by a correction factor κ, which is obtained by comparison of the detection efficiencies at both energies using MC simulations. The total number of $\tau^+\tau^-$ events $N_{\tau\tau}$ is finally given by

$$N_{\tau\tau} = \frac{n\varepsilon_{trig}^{'}\sigma_{QED}^{'}\mathcal{L}^{'}}{n^{'}\kappa\varepsilon_{trig}}. \tag{5}$$

Table I is a summary of the factors appeared in this formula for all four topologies.

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

$$B(\tau\tau) = \frac{N_{\tau\tau}^{WA} - \sigma_{Q+I}\mathcal{L}}{N_{\psi(2s)}}. \tag{6}$$

Here $N_{\tau\tau}^{WA}$ is the number of $\tau^+\tau^-$ events recorded on the resonance, which is a weighted average of four topologies listed in Table I; σ_{Q+I} is the calculated QED τ-pair cross section including interference [6]; $N_{\psi(2s)}$ is the number of produced $\psi(2s)$ events; and $\mathcal{L}$ is the accumulated luminosity at the resonance. The measurements of $N_{\psi(2s)}$ and $\mathcal{L}$ are described below.

$N_{\psi(2s)}$ is determined from a study of inclusive J/ψ produced in $\psi(2s)$ decays in the topologies $\psi(2s) \rightarrow \pi\pi J/\psi$. The J/ψ production is inferred in the recoil from the $\pi\pi$ system as shown in Fig 1. To estimate $N_{\psi(2s)}$, the PDG value for $B(\psi(2s) \rightarrow \pi\pi J/\psi)$ is used [7].

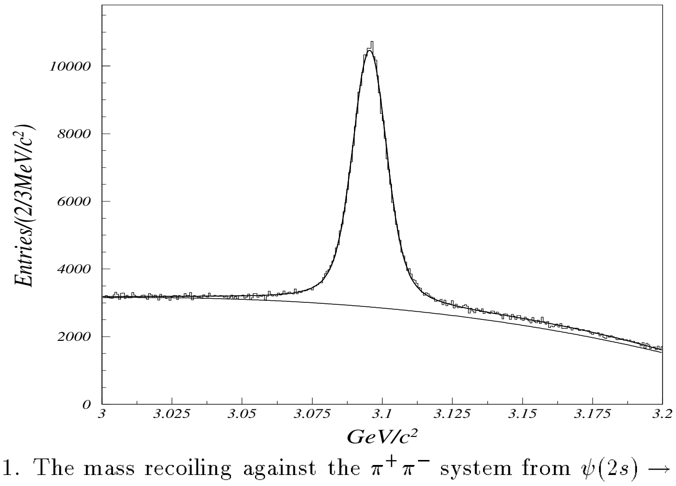

FIG. 1. The mass recoiling against the $\pi^+\pi^-$ system from $\psi(2s) \rightarrow \pi^+\pi^- J/\psi$.

$\mathcal{L}$ is determined by recording wide-angle Bhabha events at the $\psi(2s)$ in the BES detector, and is given by

$$\mathcal{L} = \frac{N_{QED}}{\sigma_{QED}\varepsilon_f\varepsilon_t\varepsilon_d}, \tag{7}$$

where N_{QED}, σ_{QED}, ε_f, 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 filter efficiency, 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/ψ, $J/\psi \rightarrow e^+e^-$, should be subtracted from the total number of events. Using the symmetrical distribution of the e^+e^- production in these decays relative to $cos\theta = 0$ as is shown in Fig. 1, it is easy to find that

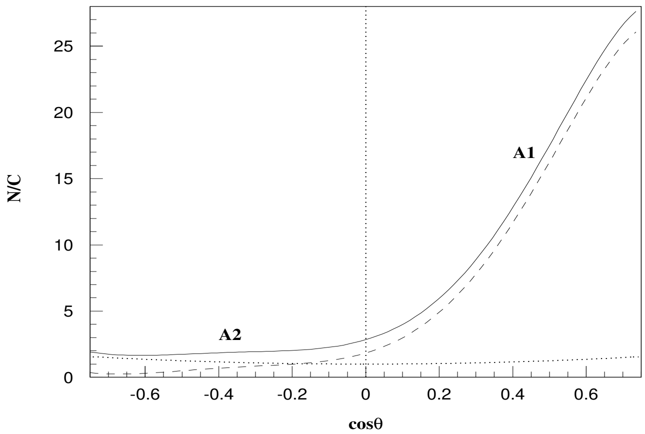

FIG. 2. Schematic of angular distributions of electrons (or positrons) produced in $e^+e^- \to e^+e^-$ at c.m. energy=3.686 GeV. The dashed curve represents the Bhabha scattering (corrected for interference); the dotted curve represents the resonant e^+e^- production of the $\psi(2s)$ and of the J/ψ from $\psi(2s) \to$ neutral J/ψ decays; the solid curve shows their sum.

$$N_{QED} = \frac{A_1 - A_2}{1 - 2\alpha}, \tag{8}$$

where A_1 and A_2 are the total number of e^+e^- events found from the area under the solid curve on the right side and left side relative to $cos\theta = 0$, respectively, and α is the fraction of Bhabha events on the left side, which is determined by a Monte Carlo simulation.

The result of this measurement is summarized in Table II. The Branching fraction of the $\psi(2s)$ decaying into $\tau^+\tau^-$ is calculated to be

$$B_{\tau\tau} = (3.2 \pm 0.6 \pm 0.6) \times 10^{-3}, \tag{9}$$

where the first error is statistical and the second is systematic. The overall relative systematic error of 18.7% includes contributions from the luminosity $\mathcal{L}$ (2.9%); the number of $\psi(2S)$ events, $N_{\psi(2S)}$ (8.7%); the number of $\tau^+\tau^-$ events, $N_{\tau\tau}^{WA}$ (5.2%), which incorporates the uncertainties in luminosity scale $\mathcal{L}^{'}$, trigger efficiencies ϵ_{trig} and $\epsilon_{trig}^{'}$, and the calculated values of $\sigma_{\rm QED}$ and $\sigma_{\rm QED}^{'}$ due to uncertainties in the c.m. energy scale and the spread in c.m. energy (11.5%).

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. (1), agrees with the previous data of B_{ee} [1] and $B_{\mu\mu}$ [2]. Assuming lepton universality, the average value of $B(\psi(2S) \to l^+l^-)$ is determined to be $(8.4 \pm 0.9) \times 10^{-3}$. The leptonic width ($\Gamma_{ee}$) of the $\psi(2S)$ has been determined by DASP and MARK I groups, and a refined value of (2.14 ± 0.21) keV is given in Ref. 3. From the relationship $\Gamma_{tot} = \Gamma_{ee}/B_{ll}$ we find $\Gamma_{tot} = (256 \pm 38)$ keV, which is consistent with the direct measurement by E760 [8] within experimental uncertainties.

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

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TABLES

TABLE I. Summary of factors used to translate observed events in four topologies into produced τ-pairs. The error in $N_{\tau\tau}$ is statistical only.

Topology	n	$n^{'}$	κ	$\sigma^{'}_{\mathrm{QED}}$(nb)	$\mathcal{L}^{'}$(pb^{-1})	$\epsilon_{trig}/\epsilon^{'}_{trig}$	$N_{\tau\tau}$
$e\mu$	90.9	152	1.041	3.27	4.68	1	8795±1171
eh	62.4	109	0.892	3.27	4.68	1	9821±1575
ee	54.7	89	0.954	3.27	4.68	1	9864±1698
μh	42.0	81	0.885	3.27	4.68	1	8969±1705

TABLE II. Numbers used to calculate $B_{\tau\tau}$. $N^{WA}_{\tau\tau}$ is obtained by weighting the $N_{\tau\tau}$ for all four topologies. The $\sigma_{\mathrm{QED+I}}$ includes interference which contributes 0.08nb. The first error is statistical and the second is systematic.

$N^{WA}_{\tau\tau}$	$\mathcal{L}$(pb^{-1})	$\sigma_{\mathrm{QED+I}}$(nb)	$N_{\psi(2S)}(10^6)$
$9258 \pm 741 \pm 481$	$2.25 \pm 0.01 \pm 0.07$	2.24	$1.33 \pm 0.00 \pm 0.12$

TABLE III. Leptonic branching fractions of the $\psi(2S)$.

	B_{ll} (10^{-3})	Reference
ee	8.8 ± 1.3	1
$\mu\mu$	7.7 ± 1.7	2
$\tau\tau$	$3.2 \pm 0.6 \pm 0.6$	Present work