First Measurement of the Branching Fraction of the Decay $\psi(2S) \to \tau^+\tau^-$

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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 $B_{\tau\tau} = (2.71 \pm 0.43 \pm 0.55) \times 10^{-3}$, 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, well satisfy 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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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 $v_l = (1-\frac{4m_l^2}{M^2_{\psi(2S)}})^{\frac{1}{2}}$, $l = e,\ \mu, \tau$. 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 result for the leptonic width of this resonance [3] [4], 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). 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 twelve-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 0.4T 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 with an uncertainty of 0.29 MeV. The spread in the center-of-mass energy of the collider is $\Delta = (1.4 \pm 0.1)$ 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.

The $\tau^+\tau^-$ events are identified by requiring that one τ decays via $e\nu\overline{\nu}$ and the other via $\mu\nu\overline{\nu}$. 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, θ_{acol}, defined as the angle between the outgoing charged tracks, is required to satisfy $10^\circ \leq \theta_{acol} \leq 170^\circ$ to reject Bhabhas, muon pairs and cosmic rays. The acoplanarity angle, θ_{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 $\theta_{acop} \geq 20^\circ$ to suppress radiative Bhabhas and radiative muon pairs. Furthermore, each track is required to satisfy $|\cos\theta| \leq 0.65$, 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 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 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 as an electromagnetic shower having energy > 60 MeV and a separation from the nearest charged track of at least 12°.

A particle identification procedure is applied to the selected events. By making use of 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 are assuming the electron hypothesis. Here, separation means { (measured value - expected value)/resolution }. Then, to identify a track as a electron we required $-4 \leq Tse \leq 0.5, -1 \leq Xse \leq 2, -4 \leq Sse \leq 4$ if its momentum is less than 0.35GeV ; $-4 \leq Tse \leq 1.5, -2 \leq Xse \leq 2, -1.5 \leq Sse \leq 4$ if its momentum is between 0.35GeV and 0.7GeV ; or $-4 \leq Tse \leq 4, -1.5 \leq Xse \leq 2, -2 \leq Sse \leq 4$ if its momentum is greater than 0.7GeV. A track is assigned as a muon if there are at least 2 hits in the muon counters.

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 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 0.24 events for data set I and 0.49 events for data set II. A Monte Carlo study on the two–photon process has also been performed; its contamination is estimated to be negligible.

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

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

Here B is the fraction of $\tau^+\tau^-$ events yielding the $e\mu$ topology, is equal to 0.06194 [6]; 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 [7]. 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%). The calculated QED τ-pair cross section including interference σ_{Q+I} is equal to $2.230nb^{-1}$ at the center-of-mass energy corresponding to the $\psi(2S)$ resonance [8] ; $N_{\psi(2S)}$ is the number of produced $\psi(2S)$ events; and $\mathcal{L}$ is the accumulated luminosity at the resonance.

The number of produced $\psi(2S)$ events $N_{\psi(2S)}$ is determined from a study of inclusive J/ψ produced in $\psi(2S)$ decays in the topology $\psi(2S) \to \pi^+\pi^- J/\psi$ [9]. The number of produced $\pi^+\pi^- J/\psi$ events, $N_{\pi\pi J/\psi}$ is inferred in the recoil from the $\pi^+\pi^-$ system (Fig. 1). To estimate $N_{\psi(2S)}$, the PDG value for $B(\psi(2S) \to \pi^+\pi^- J/\psi) = (31.0 \pm 2.8)\%$ [6] is used.

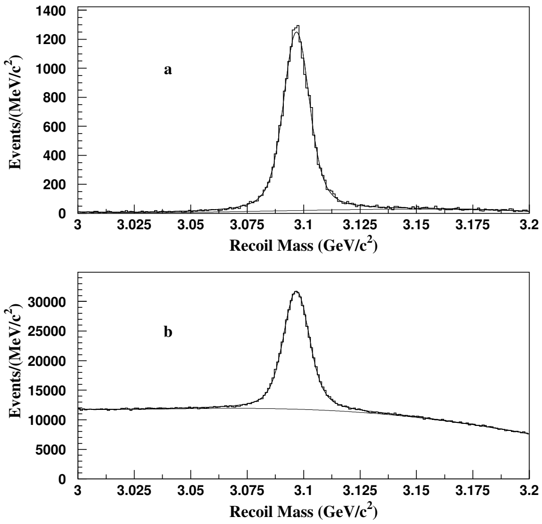

FIG. 1. The mass recoiling against the $\pi^+\pi^-$ system from $\psi(2S) \to \pi^+\pi^- J/\psi$: (a) exclusive $J/\psi \to l^+l^-$ events; (b) inclusive J/ψ events.

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

$$\mathcal{L} = \frac{N_{QED}}{\sigma_{QED}\epsilon_t\epsilon_d}, \tag{4}$$

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 $\psi(2S) \to e^+e^-$ as well as from $\psi(2S) \to$ neutral J/ψ, $J/\psi \to e^+e^-$, 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 $\cos\theta = 0$ as shown in Fig. 2, a relation for the number of Bhabha events can be obtained

$$N_{QED} = \frac{A_1 - A_2}{1 - 2\alpha}, \tag{5}$$

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.

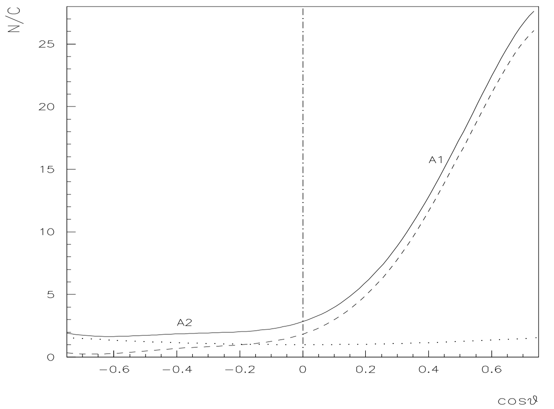

FIG. 2. Schematic of angular distributions of electrons (or positrons) produced in $e^+e^- \rightarrow e^+e^-$ at c.m. energy=3.686 GeV. The dashed curve represents the Bhabha scattering (corrected for interference); the dotted curve represents the resonant e^+e^- production of the $\psi(2S)$ and of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

The results of this measurement are summarized in Table I and Table 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

$$B_{\tau\tau} = (2.71 \pm 0.43 \pm 0.55) \times 10^{-3}, \tag{6}$$

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 values of $\sigma_{\rm QED}$ due to uncertainties in the c.m. energy scale and the spread in c.m. energy (10.8%).

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 $B_{\mu\mu}$ [6]. Assuming lepton universality, the average value B_{ll} is determined to be $(8.4 \pm 1.0) \times 10^{-3}$. The leptonic width (Γ_{ee}) of the $\psi(2S)$ has been determined to be (2.12 ± 0.18) keV [6]. From the relationship $\Gamma_{tot} = \Gamma_{ee}/B_{ll}$ we find $\Gamma_{tot} = (252 \pm 37)$ keV, which is consistent with the direct measurement value (306 ± 39) keV by E760 [10] 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 $B_{\mu\mu}$, well satisfy the relation predicted by the sequential lepton hypothesis. Combining these values we have calculated the total width for this resonance.

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TABLES

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	$\mathcal{L}(\mathrm{pb}^{-1})$	$N_{\pi\pi J/\psi}(10^6)$	$N_{\psi(2S)}(10^6)$
I	77	0.27	0.1449	$2.123 \pm 0.015 \pm 0.051$	$0.4293 \pm 0.0017 \pm 0.0076$	$1.385 \pm 0.005 \pm 0.127$
II	140	0.49	0.1439	$3.929 \pm 0.019 \pm 0.098$	$0.7980 \pm 0.0023 \pm 0.0092$	$2.574 \pm 0.007 \pm 0.234$
Total	217	0.76	0.1442	$6.052 \pm 0.024 \pm 0.149$	$1.227 \pm 0.003 \pm 0.017$	$3.959 \pm 0.009 \pm 0.362$

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	$8.73 \pm 1.39 \pm 1.57$	$2.71 \pm 0.43 \pm 0.55$

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	10.3 ± 3.5	$7.0 \pm 1.1 \pm 1.4$