MEASUREMENT OF THE MASS OF THE τ LEPTON[*]

J. Z. Bai[a] O. Bardon[f] R. A. Becker-Szendy[f] T. H. Burnett[j] J. S. Campbell[b] S. J. Chen[a]
S. M. Chen[a] Y. Q. Chen[a] Z. D. Cheng[a] J. A. Coller[b] R. F. Cowan[f] H. C. Cui[a] X. Z. Cui[a]
H. L. Ding[a] Z. Z. Du[a] W. Dunwoodie[g] C. Fang[a] M. J. Fero[f] M. L. Gao[a] S. Q. Gao[a] W. X. Gao[a]
Y. N. Gao[a] J. H. Gu[a] S. D. Gu[a] W. X. Gu[a] Y. N. Guo[a] Y. Y. Guo[a] Y. Han[a] M. Hatanaka[c]
J. He[a] D. G. Hitlin[c] G. Y. Hu[a] T. Hu[a] D. Q. Huang[a] Y. Z. Huang[a] J. M. Izen[i] Q. P. Jia[a]
C. H. Jiang[a] Z. J. Jiang[a] A. S. Johnson[b] L. A. Jones[c] M. H. Kelsey[c] Y. F. Lai[a] P. F. Lang[a]
A. Lankford[d] F. Li[a] J. Li[a] P. Q. Li[a] Q. M. Li[a] R. B. Li[a] W. Li[a] W. D. Li[a] W. G. Li[a] Y. S. Li[a]
S. Z. Lin[a] H. M. Liu[a] Q. Liu[a] R. G. Liu[a] Y. Liu[a] B. Lowery[j] J. G. Lu[a] D. H. Ma[a] E. C. Ma[a]
J. M. Ma[a] M. Mandelkern[d] H. Marsiske[f] H. S. Mao[a] Z. P. Mao[a] X. C. Meng[a] H. L. Ni[a]
L. J. Pan[a] J. H. Panetta[c] F. C. Porter[c] E. N. Prabhakar[c] N. D. Qi[a] Y. K. Que[a] J. Quigley[f]
G. Rong[a] B. Schmid[d] J. Schultz[d] J. T. Shank[b] Y. Y. Shao[a] D. L. Shen[a] H. Y. Sheng[a] H. Z. Shi[a]
A. Smith[d] E. Soderstrom[f] X. F. Song[a] D. P. Stoker[d] H. S. Sun[a] J. Synodinos[f] W. H. Toki[c]
G. L. Tong[a] E. Torrence[f] L. Z. Wang[a] M. Wang[a] P. Wang[a] P. L. Wang[a] T. J. Wang[a]
Y. Y. Wang[a] J. S. Whitaker[b] R. J. Wilson[b] W. J. Wisniewski[h] X. D. Wu[a] D. M. Xi[a] X. M. Xia[a]
P. P. Xie[a] X. X. Xie[a] R. S. Xu[a] Z. Q. Xu[a] S. T. Xue[a] R. K. Yamamoto[f] J. Yan[a] W. G. Yan[a]
C. M. Yang[a] C. Y. Yang[a] H. B. Yao[a] M. H. Ye[a] S. Z. Ye[a] Z. Q. Yu[a] B. Y. Zhang[a] C. C. Zhang[a]
D. H. Zhang[a] H. L. Zhang[a] H. Y. Zhang[a] J. W. Zhang[a] L. S. Zhang[a] S. Q. Zhang[a] Y. Zhang[a]
D. X. Zhao[a] M. Zhao[a] P. D. Zhao[a] W. R. Zhao[a] J. P. Zheng[a] L. S. Zheng[a] Z. P. Zheng[a]
G. P. Zhou[a] H. S. Zhou[a] L. Zhou[a] L. Zhou[a] X. F. Zhou[a] Y. H. Zhou[a] Q. M. Zhu[a] Y. C. Zhu[a]
Y. S. Zhu[a] and G. Zioulas[d]

[a] Institute of High Energy Physics, Beijing 100039, People's Republic of China.
[b] Boston University, Boston, MA 02215, USA.
[c] California Institute of Technology, Pasadena, CA 91125, USA.
[d] University of California, Irvine, CA 92717, USA.
[e] Colorado State University, Fort Collins, CO 80523, USA.
[f] Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
[g] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA.
[h] Superconducting Super Collider Laboratory, Dallas, TX 75237–3946, USA.
[i] University of Texas at Dallas, Richardson, TX 75083–0688, USA.
[j] University of Washington, Seattle, WA 98195, USA.

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ABSTRACT

The mass of the τ lepton has been measured at the Beijing Electron Positron Collider using the Beijing Spectrometer. A search near threshold for $e^+e^- \rightarrow \tau^+\tau^-$ was performed. Candidate events were identified by requiring that one τ decay via $\tau \rightarrow e\nu\bar{\nu}$, and the other via $\tau \rightarrow \mu\nu\bar{\nu}$. The mass value, obtained from a fit to the energy dependence of the $\tau^+\tau^-$ cross section, is $m_\tau = 1776.9^{+0.4}_{-0.5} \pm 0.2$ MeV.

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For a conventional charged lepton l, the electronic branching ratio B_l^e, lifetime τ_l, mass m_l, and weak coupling constant $G_{l \to e\nu\bar{\nu}}$ are related by

$$\frac{B_l^e}{\tau_l} = \frac{G_{l \to e\nu\bar{\nu}}^2}{192\pi^3} m_l^5 \quad , \tag{1}$$

up to small radiative and electroweak corrections. Equation (1) then implies the following relationship among the above parameters for the τ and μ leptons:

$$\left(\frac{G_{\tau \to e\nu\bar{\nu}}}{G_{\mu \to e\nu\bar{\nu}}}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B_\tau^e}{B_\mu^e} \frac{\tau_\mu}{\tau_\tau} \quad . \tag{2}$$

Particle Data Group[1] (PDG) averages for the above quantities yield $(G_{\tau \to e\nu\bar{\nu}}/G_{\mu \to e\nu\bar{\nu}})^2 = 0.941 \pm 0.025$, implying a 2.4 standard deviation disagreement with lepton universality[2]. Note that the τ mass enters to the fifth power in this test of lepton university.

A measurement of the $\tau^+\tau^-$ production cross section in the region most sensitive to the τ mass—a few MeV around threshold—provides the opportunity to measure the τ mass with greatly improved precision. This paper presents such a measurement made using the Beijing Spectrometer (BES) at the Beijing Electron Positron Collider (BEPC). The $\tau^+\tau^-$ events are identified by means of the $e\mu$ topology, which provides the best combination of high detection efficiency and low background; the mass value is obtained from a fit to the energy dependence of the cross section. The measurement is independent of the ν_τ mass.

The BEPC[3] operates in the 3 to 5 GeV center-of-mass energy range. Near $\tau^+\tau^-$ threshold, the peak luminosity is 5×10^{30} cm^{-2} s^{-1}, the luminosity-weighted uncertainty in the mean center-of-mass energy is 0.10 MeV, and the spread in the center-of-mass energy of the collider is ≈ 1.4 MeV. The absolute energy scale and energy spread are determined by interpolation between the results of repeated scans of the J/ψ and $\psi(2S)$ resonances.

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The BES is a solenoidal detector[3] with a 0.4 T magnetic field. Charged track reconstruction is performed by means of a cylindrical drift chamber which provides solid angle coverage of 85% of 4π. The momentum resolution is $\sigma_p/p = 0.021\sqrt{1+p^2}$ (p in GeV/c). Measurements of dE/dx with resolution 8.5% allow particle identification. An inner drift chamber is used for trigger purposes. Scintillation counters measure the time-of-flight of charged particles over 76% of 4π with a Bhabha resolution of 330 ps. A cylindrical twelve-radiation-length Pb/gas electromagnetic calorimeter operating in limited streamer mode covering 80% of 4π achieves energy resolution $\sigma_E/E = 0.25/\sqrt{E(\text{GeV})}$, and spatial resolution $\sigma_\phi = 4.5$ mrad, $\sigma_z = 2$ cm. End cap time-of-flight counters and shower counters are not used in this analysis. Finally, 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.

In the data analysis, the event selection for $e\mu$ candidates requires: (1) exactly two oppositely charged tracks having momentum between 350 MeV/c and the maximum for an electron from τ decay; (2) each track's point of closest approach to the intersection point to satisfy $|x| < 1.5$ cm, $|y| < 1.5$ cm, and $|z| < 15$ cm; (3) $2.5° < \theta_{\text{acol}} < 177.5°$, $\theta_{\text{acop}} > 10°$(see Reference 4), and $(\theta_{\text{acol}} + \theta_{\text{acop}}) > 50°$; (4) no isolated photons[5]; (5) one track well identified as a muon in the muon-counter, with calorimeter energy < 500 MeV, and the other track well identified as an electron using a combination of calorimeter, dE/dx and time-of-flight information.

Monte Carlo simulations yield a detection efficiency of $\approx 14\%$ for these selection criteria, independent of energy in the threshold region. The background is estimated by applying the same requirements to five million events from a data sample taken at the J/ψ energy; seven events meet these criteria, corresponding to a background of 0.12 events in the entire $\tau^+\tau^-$ sample.

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The likelihood function used to estimate the τ mass incorporates the $\tau^+\tau^-$ cross section near threshold. Including the center-of-mass energy spread Δ, initial state radiation[6] $F(x,W)$, and vacuum polarization corrections[7] $\Pi(W)$, the cross section is

$$\sigma(W,m_\tau) = \frac{1}{\sqrt{2\pi}\Delta}\int\limits_0^\infty dW' e^{-\frac{(W-W')^2}{2\Delta^2}}\int\limits_0^{1-\frac{4m_\tau^2}{W'^2}} dx\, F(x,W')\sigma_1(W'\sqrt{1-x},m_\tau) \quad , \quad (3)$$

where σ_1 is

$$\sigma_1(W,m_\tau) = \frac{4\pi\alpha^2}{3W^2}\frac{\beta(3-\beta^2)}{2}\frac{F_c(\beta)F_r(\beta)}{[1-\Pi(W)]^2} \quad , \quad (4)$$

W is the center-of-mass energy, and $\beta = \sqrt{1-(2m_\tau/W)^2}$. The Coulomb interaction and final state radiation corrections are described[8] by the functions $F_c(\beta)$ and $F_r(\beta)$.

The likelihood function is a product of Poisson distributions, one for each center-of-mass energy. At each point, the number of expected $e\mu$ events $\langle N\rangle$, is given by:

$$\langle N\rangle = [\epsilon\, B\, \sigma(W,m_\tau) + \sigma_B]\mathcal{L} \quad . \quad (5)$$

Here, ϵ is the detection efficiency, B is the product branching fraction for $\tau^+\tau^-$ to $e\mu$, $\mathcal{L}$ is the integrated luminosity, and σ_B is the effective background cross section estimated from the J/ψ data sample ($\sigma_B = 0.024$ pb).

Since the range of center-of-mass energies where the $\tau^+\tau^-$ cross section is most sensitive to the τ mass is of the order of the beam energy spread around $\tau^+\tau^-$ threshold, it is important to devise a running strategy to maximize the integrated luminosity in this region. The beam energy is set initially assuming the world average for the τ mass; in this case, the PDG value 1784.1 MeV.[1] Then, after each 250–400 nb^{-1} of integrated luminosity, a new estimate of the mass is made using all the

data accumulated to that point; in this way, a new prediction of the most sensitive energy at which to run is obtained. The energy is changed to this new value if the difference is more than the BEPC step size (≈ 0.4 MeV). Following this strategy, an integrated luminosity of ≈ 4.3 pb^{-1} has been accumulated at ten energies within a range of 24 MeV. It has been verified by Monte Carlo simulation that this data-driven search strategy provides an unbiased measurement.

The sequence of energies is shown in Figure 1; the corresponding data are summarized in Table 1.[9] The ten-step search yielded seven $e\mu$ events. The eleventh and twelfth points in Table 1, taken well above threshold where the cross section varies slowly with energy, provide an improved estimate of the absolute $\tau^+\tau^-$ cross section.

In order to account for uncertainties in the efficiency ϵ, the branching fraction product and the luminosity, ϵ is treated as a free parameter in a two-dimensional maximum-likelihood fit for m_τ and ϵ to the data of Table 1. The estimates obtained are $m_\tau = 1776.9$ MeV and $\epsilon = 14.1\%$. The uncertainty in ϵ is equivalent to the uncertainty in the absolute normalization, and is treated as a source of systematic error. The statistical error[10] in m_τ, $^{+0.4}_{-0.5}$ MeV, is determined from the one-parameter likelihood function with ϵ fixed to 14.1% (Figure 2). The efficiency-corrected cross section data as a function of corrected beam energy and the curve which results from the likelihood fit are shown in Figure 2. The quality of the fit is checked by forming the likelihood ratio λ, with result[11] $-2\ell n\,\lambda = 3.6$.

Four independent sources of systematic error are considered: uncertainties in the product $\epsilon B \mathcal{L}$, in the absolute beam energy scale, in the beam energy spread, and in the background.

The systematic uncertainty in $\epsilon B \mathcal{L}$ is determined by fixing m_τ at its best-estimate value and finding the values of ϵ corresponding to $\pm 1\sigma$ variations in the likelihood

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function; these efficiencies are 18.3% and 10.6%. Fixing the efficiency to each of these values in turn and fitting for m_τ yields changes in the predicted mass of $\Delta m_\tau = {}^{+0.16}_{-0.20}$ MeV.

The energy scale is determined from several scans of the J/ψ and $\psi(2S)$ performed during the search (see Figure 1). The reproducibility of the fits to these scans, together with the other uncertainties listed in Table 2, yields a systematic uncertainty[12] of $\Delta m_\tau = \pm 0.09$ MeV.

Fits to the two resonances were also used to measure the beam energy spread and its variation with center-of-mass energy and beam current. The uncertainty in center-of-mass energy spread is ± 0.08 MeV, yielding a systematic error $\Delta m_\tau = \pm 0.02$ MeV.

Finally, the systematic error due to uncertainty in the background is estimated from the 1σ Poisson errors on the seven J/ψ background events and the uncertainty in the hadronic cross section at $\tau^+\tau^-$ threshold. The resulting uncertainty is $\Delta m_\tau = \pm 0.01$ MeV.

These independent systematic errors are added in quadrature to yield a total systematic error of $\Delta m_\tau = {}^{+0.18}_{-0.22}$ MeV.

In conclusion, using a maximum likelihood fit to $\tau^+\tau^-$ cross section data near threshold, the mass of the τ lepton has been measured as $m_\tau = 1776.9^{+0.4}_{-0.5} \pm 0.2$ MeV, where the first error is statistical and the second systematic. This result is 7.2 MeV below the PDG average[1] ($1784.1^{+2.7}_{-3.6}$ MeV) and has significantly smaller errors[13] Inserting this new value in Equation (2), the coupling strength ratio becomes

$$\left(\frac{G_{\tau \to e\nu\bar{\nu}}}{G_{\mu \to e\nu\bar{\nu}}} \right)^2 = 0.960 \pm 0.024 \quad , \tag{6}$$

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so that the deviation from lepton universality is reduced from 2.4 to 1.7 standard deviations (see Figure 3). It should be noted also that this new result for m_τ yields a reduction in the upper limit on m_{ν_τ} (see reference 13).

Acknowledgments

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[2] W. J. Marciano, *Phys. Rev.* **D45**, 721 (1992). The measurements quoted in this reference have been superseded by Reference 1.

[3] M. H. Ye and Z. P. Zheng, in *Proceedings of the 1989 International Symposium on Lepton and Photon Interactions at High Energies* (Stanford University, Stanford, 1989), p. 122.

[4] Acoplanarity, θ_{acop}, is defined as the angle between the planes spanned by the beam direction and the momentum vector of e and μ, respectively. Acollinearity, θ_{acol}, is defined as the angle between the momentum vectors of e and μ.

[5] An isolated photon has an energy > 60 MeV and is separated from the nearest charged track by $> 12°$.

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[9] Δ was determined according to the equation $\Delta = (A\bar{I} + B)(CW^2 + D)$, where $\bar{I}$ is the average beam current. A, B, C and D are fitted to beam current measurements and to measurements of the energy spreads at the J/ψ and $\psi(2S)$ resonances.

[10] It has been verified by simulation that this uncertainty corresponds to a 68% confidence interval.

[11] In the large statistics limit, $-2\ell n\,\lambda$ would obey a χ^2 distribution for ten degrees of freedom.

12 Assuming a linear relation between measured energy W_M, and the corrected value W, the latter is given by:

$$W = T_\psi + (W_M - M_\psi) \left(\frac{T_{\psi'} - T_\psi}{M_{\psi'} - M_\psi} \right)$$

in the notation of Table 2. At $\tau^+\tau^-$ threshold the resulting mass scale correction is $W - W_M = -0.74$ MeV, with corresponding uncertainty $\delta W = 0.18$ MeV.

13 The Argus Collaboration has also reported (H. Albrecht *et al.*, Preprint DESY 92–086, 1992) a new measurement of the τ mass, $m_\tau = 1776.3 \pm 2.4 \pm 1.4$ MeV.

Table 1: A chronological summary of the $\tau^+\tau^-$ data.

Scan Point	$W/2$ (MeV)	Δ (MeV)	$\mathcal{L}$ (nb^{-1})	N ($e\mu$ events)
1	1784.19	1.34	245.8	2
2	1780.99	1.33	248.9	1
3	1772.09	1.36	232.8	0
4	1776.57	1.37	323.0	0
5	1778.49	1.44	322.5	2
6	1775.95	1.43	296.9	0
7	1776.75	1.47	384.0	0
8	1776.98	1.47	360.8	1
9	1776.45	1.44	794.1	0
10	1776.62	1.40	1109.1	1
11	1799.51	1.44	499.7	5
12	1789.55	1.43	250.0	2

Table 2: Contributions to the uncertainty in the energy scale.

Quantity	Error (MeV)
W_M : BEPC measured center-of-mass energy	$\delta W_M = 0.10$
M_ψ : BEPC value for J/ψ mass	$\delta M_\psi = 0.18$
$M_{\psi'}$: BEPC value for $\psi(2S)$ mass	$\delta M_{\psi'} = 0.15$
T_ψ : PDG value for J/ψ mass[1]	$\delta T_\psi = 0.09$
$T_{\psi'}$: PDG value for $\psi(2S)$ mass[1]	$\delta T_{\psi'} = 0.10$

FIGURE CAPTIONS

1. (a) The convergence of the predicted mass with each consectutive scan point.

   (b) The integrated luminosity accumulated at each point.

2. (a) The center-of-mass energy dependence of the $\tau^+\tau^-$ cross section resulting from the likelihood fit (curve), compared to the efficiency-corrected data. The error bar on each data point is computed by integrating the Poisson likelihood function to obtain the interval containing 68% of the area. It should be emphasized that the curve does not result from a direct fit to these data points.

   (b) An expanded version of (a), in the immediate vicinity of $\tau^+\tau^-$ threshold.

   (c) The dependence of the logarithm of the likelihood function on m_τ, with efficiency fixed at 14.1%.

3. The variation of τ_τ with B_τ^e, given by Equation 1 under the assumption of lepton universality; the $\pm 1\sigma$ bands obtained using m_τ from this experiment (solid lines) and using the PDG value (dashed lines) are shown in comparison to the point corresponding to the PDG values (1σ error bars).
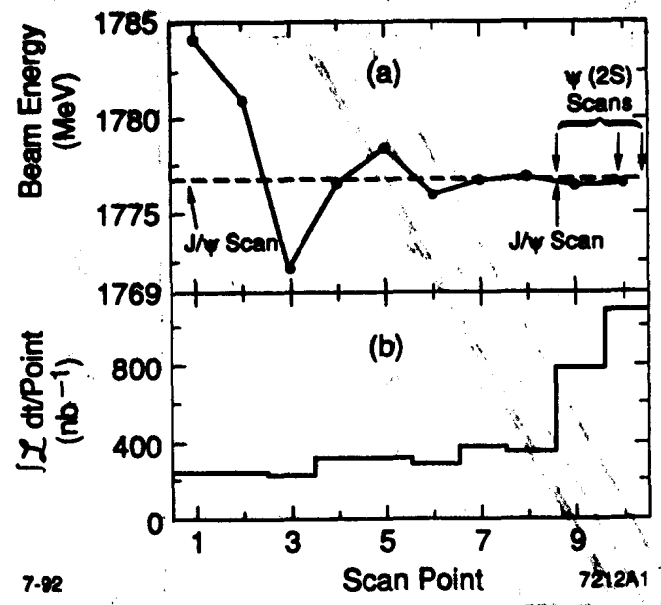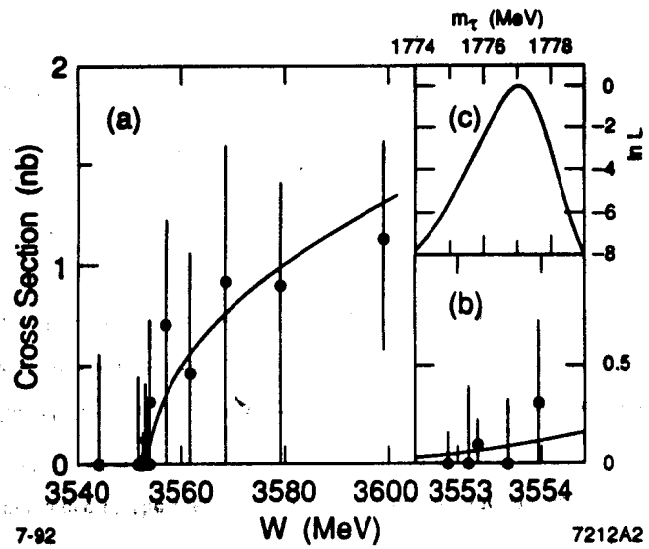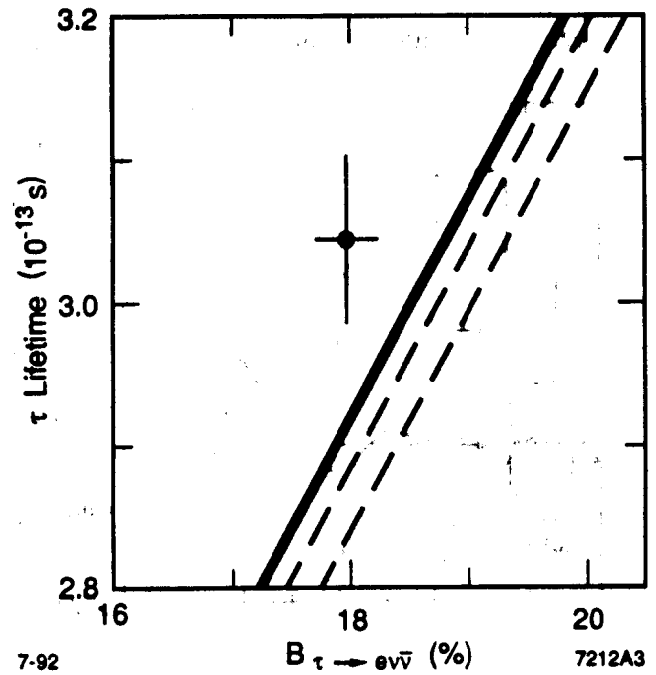
Fig. 1

Fig. 2

Fig. 3