Direct Measurement of the J/ψ Leptonic Branching Fraction

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The Mark III Collaboration has measured the J/ψ leptonic branching fractions using the process $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$. The results are $B(J/\psi \to e^+e^-) = (5.92 \pm 0.15 \pm 0.20)\%$ and $B(J/\psi \to \mu^+\mu^-) = (5.90 \pm 0.15 \pm 0.19)\%$, where the first error is statistical and the second is systematic. Assuming lepton universality, the leptonic branching fraction of the J/ψ is $(5.91 \pm 0.11 \pm 0.20)\%$. This result is used to obtain the strong coupling constant α_s and the QCD scale factor $\Lambda_{\overline{\rm MS}}$ ($\overline{\rm MS}$ denotes the modified minimal subtraction scheme).

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Most experiments that observe the J/ψ detect its presence only through its leptonic decays. Knowledge of the J/ψ leptonic branching fractions is therefore necessary to determine the total number of produced J/ψ's in those experiments. These branching fractions may also be used to estimate the strong coupling constant α_s and the corresponding quantum chromodynamics (QCD) scale factor $\Lambda_{\overline{\rm MS}}^{(n_f)}$, where n_f is the effective number of quark flavors in the experiment [1,2] and $\overline{\rm MS}$ denotes the modified minimal subtraction scheme. We present herein a direct measurement of the J/ψ leptonic branching fractions, using the ratio of the measured rates of the following exclusive and inclusive processes:

$$\psi(2S) \to \pi^+\pi^- J/\psi, \quad J/\psi \to l^+l^-, \tag{1}$$

$$\psi(2S) \to \pi^+\pi^- J/\psi, \quad J/\psi \to \text{anything}, \tag{2}$$

where l is either an electron or a muon.

The data were collected with the Mark III detector [3] in two separate running periods at the SLAC e^+e^- storage ring SPEAR. The data were collected at a center-of-mass energy corresponding to the $\psi(2S)$ resonance. In this analysis, the main drift chamber, supplemented by a new vertex chamber [4] for the second period, is used to measure the momenta of the charged tracks. The barrel calorimeter and the muon chambers are used for particle identification. Because of the different configuration of the detector in the two periods, the two distinct data sets, A and B, require that separate Monte Carlo samples be generated.

For processes (1) and (2), each pion candidate track is required to have momentum less than 0.6 GeV/c, transverse momentum greater than 0.1 GeV/c, and $|\cos\theta|$ less than 0.8, where θ is the polar angle relative to the beam axis. The two-pion invariant mass is required to be greater than 0.36 GeV/c^2.

For process (1), the total number of charged tracks is required to be four with net charge zero [5]. Each lepton candidate track is required to have momentum greater than 1 GeV/c and $|\cos\theta|$ less than 0.7. The electron candidates are required to have shower energies greater than 0.8 GeV; muon candidates are identified using hits in the muon chambers [6].

We define the mass recoiling against the $\pi^+\pi^-$ system as

$$M_{\rm recoil} \equiv [(m_{\psi(2S)} - E_{\pi^+} - E_{\pi^-})^2 - (\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})^2]^{1/2},$$

where $E_\pi = (m_\pi^2 + p_\pi^2)^{1/2}$. The $M_{\rm recoil}$ values for processes

(1) and (2) are required to be in the interval from 3.0 to 3.2 GeV/c^2. The $M_{\rm recoil}$ distributions for process (1), shown in Fig. 1, are background free. The total numbers of these events, n_1, are listed in Table I. The events in the tails have dilepton masses consistent with the mass of the J/ψ. The line shape for the J/ψ is determined by fitting the events in Fig. 1 with two Gaussian functions and a quadratic polynomial.

The $M_{\rm recoil}$ distributions for process (2), shown in Fig. 2, include all combinations of $\pi^+\pi^-$ candidates in the events. We fitted these distributions using the J/ψ signal shape determined from Fig. 1, together with an additional quadratic polynomial term to model the background. The total numbers of signal events, n_2, from the fit are listed in Table I.

The J/ψ leptonic branching fraction is $(n_1/\epsilon_1)/(n_2/\epsilon_2)$, where ϵ_1 and ϵ_2 are the detection efficiencies for each process. To obtain ϵ_1, we assume that process (1) occurs via the sequential two-body decays: $\psi(2S)\to X+J/\psi$, $X\to\pi^+\pi^-$, and $J/\psi\to l^+l^-$. We generate Monte Carlo samples using the X mass distribution [7]:

$$\frac{dN}{dm_X}\propto(m_X^2-4m_\pi^2)^2(m_X^2-4m_\pi^2)^{1/2}[(m_{\psi(2S)}^2-m_{J/\psi}^2-m_X^2)^2-4m_{J/\psi}^2m_X^2]^{1/2},$$

with isotropic angular distributions for the J/ψ and the charged pions, and a $1+\cos^2\theta_l^*$ distribution [8] for the lepton. In this Monte Carlo simulation, all angles are defined in the decay particle's helicity frame. We also include the effects of final-state radiation [9], energy loss, and decays of the charged pions. A comparison between the data and the Monte Carlo samples is shown in Fig. 3.

The trigger and reconstruction efficiency for the $\pi^+\pi^-$ system in process (2), ϵ_2, depends on the J/ψ charged-track multiplicity. We estimate the multiplicity distribution by measuring the number of charged tracks for events in the J/ψ peak region in Fig. 2 and subtracting the averaged multiplicity distribution from background regions above and below the peak. The resulting multiplicity distribution is consistent with measurements from our J/ψ data sample [10]. The estimation of the efficiency for each charged-track multiplicity is obtained by generating Monte Carlo samples with decays of the J/ψ into different numbers of charged and neutral points [11]. The efficiency ϵ_2, shown in Table I, is obtained by weighting the efficiencies for different charged-track multiplicities according to the measured charged-track multiplicity distributions.

The systematic error on the branching fractions arises from several sources. The effects of different selection criteria are estimated by varying the criteria and observing changes in the branching fractions. The changes caused by pion selection criteria cancel in the ratio and do not affect the branching fractions. For the leptons, varying the $|\cos\theta|$ criteria from 0.8 to 0.5 and the momentum criteria from 1.0 to 1.3 GeV/c each contributes a fractional error of 1%. The identification criterion for muons was changed from the requirement of signals in the muon chambers to the requirement of a 0.5-GeV maximum shower energy in the barrel calorimeter [12]. The shower energy requirement for electrons in the barrel calorimeter was varied by 0.1 GeV around the nominal 0.8-GeV cut. The relative systematic errors on the branching fractions from these changes in the identification criteria are less than 0.5% for muons and 0.2% for electrons.

Other contributions to the systematic error arise from the procedures for obtaining efficiencies, fit results, and background estimates. The uncertainty in the ϵ_1 measurement is obtained by the following procedure. Events containing two pions and at least one identified lepton are isolated. The efficiency for observing the second lepton is then obtained from this sample. By comparing the efficiencies determined from this method and the Monte Carlo calculation, the contribution to the systematic error

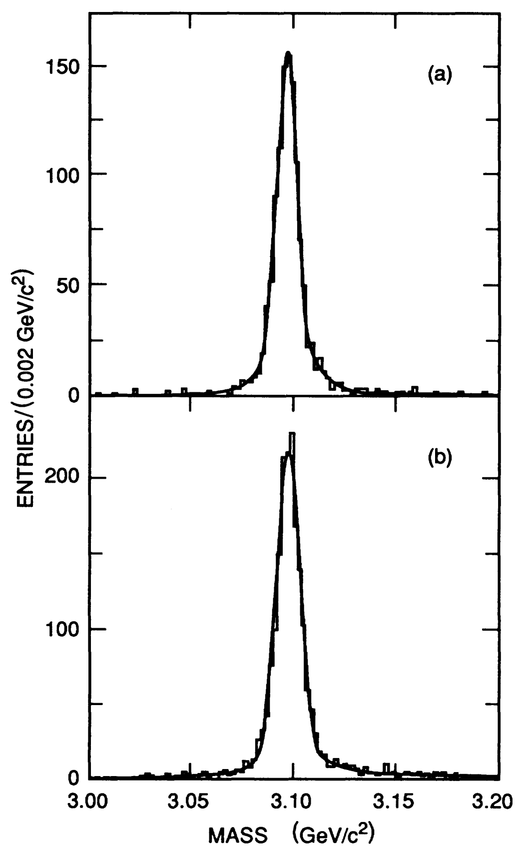

FIG. 1. The $M_{\rm recoil}$ distribution for process (1); a fit to the spectrum with two Gaussian functions and a quadratic polynomial term is shown as a solid curve. (a) Data set A. (b) Data set B. The non-Gaussian tails visible in (a) and (b) are reproduced by the Monte Carlo samples.

TABLE I. Measured results for the two different running periods. The efficiency, ϵ_1, for the muon mode of period B is noticeably lower than that for period A due to some inoperative channels in the muon chambers during running period B. In general, the efficiencies in period B are lower than those of period A because of inoperative channels in the main drift chambers for period B.

Period	Lepton type	n_1	n_2	ϵ_1	ϵ_2	B (%)
A	e	615	20230 ± 180	0.266	0.523	$5.98 \pm 0.25 \pm 0.20$
A	μ	605	20230 ± 180	0.263	0.523	$5.95 \pm 0.25 \pm 0.20$
B	e	1008	33500 ± 260	0.262	0.513	$5.89 \pm 0.19 \pm 0.19$
B	μ	897	33500 ± 260	0.234	0.513	$5.87 \pm 0.20 \pm 0.19$

for observing both leptons is estimated to be 2%. The uncertainty in the ϵ_2 measurement is obtained by varying the model of the J/ψ multiplicity distribution, and is estimated to be 2%. The fitting procedure to obtain the total number of J/ψ's contributes 1%. Potential background processes such as $\psi(2S) \to \eta J/\psi$, with $\eta \to \pi^0\pi^+\pi^-$ or $\eta \to \gamma\pi^+\pi^-$, and those with photon conversions, are negligible. Adding all of these contributions in quadrature, the fractional systematic error in the measurements of the branching fractions is 3.3%.

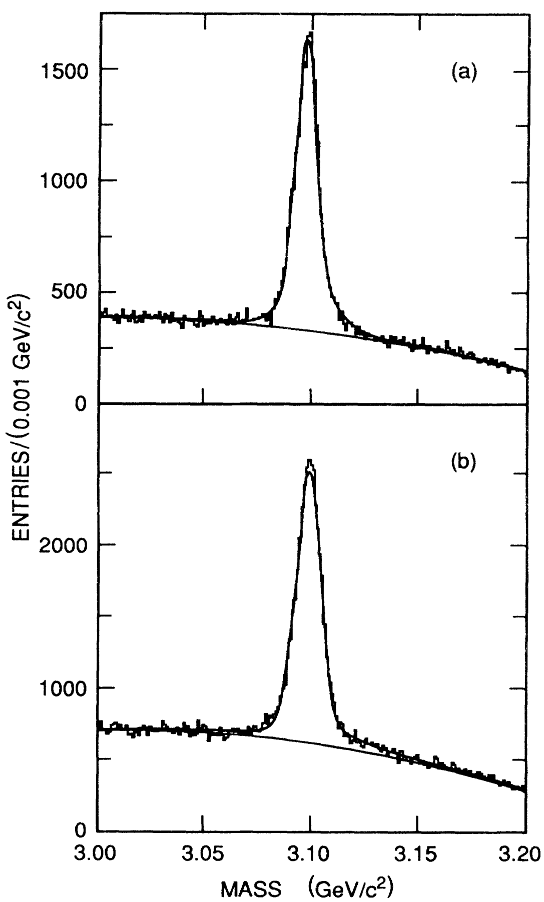

FIG. 2. The $M_{\rm recoil}$ distribution for process (2); a fit using the same signal shape as in Fig. 1, with an additional quadratic polynomial background term, is shown as a solid curve. (a) Data set A. (b) Data set B.

Combining the results from the two different running periods, we obtain

$$B(J/\psi \to e^+e^-) = (5.92 \pm 0.15 \pm 0.20)\% ,$$

$$B(J/\psi \to \mu^+\mu^-) = (5.90 \pm 0.15 \pm 0.19)\% .$$

Assuming lepton universality, we obtain [13] $B(J/\psi \to l^+l^-) = (5.91 \pm 0.11 \pm 0.20)\%$.

The experimental ratio of quarkonium annihilation rates,

$$[\Gamma(\text{quarkonium} \to ggg)]/[\Gamma(\text{quarkonium} \to \mu^+\mu^-)] ,$$

can be used in the framework of QCD [14] to determine the strong couping constant α_s. We follow the prescription of Ref. [2] and include the effects of relativistic corrections with a factor parametrized as $1+\mathcal{A}v^2/c^2$. Using the QCD relation between $\alpha_s(\mu)$ and $\Lambda^{(4)}_{\overline{\rm MS}}$, we fit the two ratios $[\Gamma(J/\psi \to ggg)]/[\Gamma(J/\psi \to \mu^+\mu^-)]$ and $[\Gamma(\Upsilon(1S) \to ggg)]/[\Gamma(\Upsilon(1S) \to \mu^+\mu^-)]$ to determine

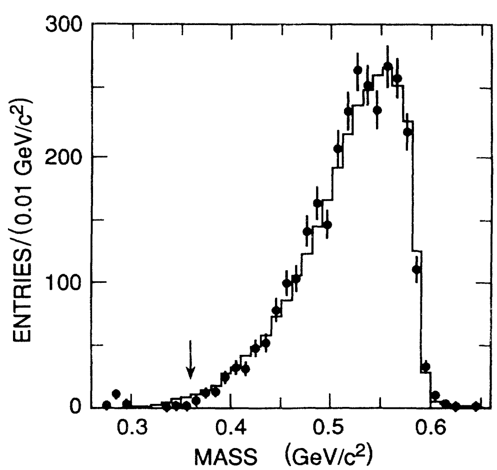

FIG. 3. The $\pi^+\pi^-$ invariant mass distribution for events from process (1) for the combined data sets (black dots) and the combined Monte Carlo samples (solid histogram). The two-pion invariant mass cut of 0.36 GeV/c^2 is indicated by the vertical arrow.

[15] $\mathcal{A}$ and $\Lambda_{\overline{\rm MS}}^{(4)}$. From this value of $\Lambda_{\overline{\rm MS}}^{(4)}$, $\alpha_s(m_c)$ and $\alpha_s(m_b)$ are then obtained. Our results are

$$\Lambda_{\overline{\rm MS}}^{(4)}=240\pm 10\ \text{MeV}\,,$$

$$\alpha_s(m_c=1.5\ \text{GeV}/c^2)=0.30\pm 0.01\,,$$

$$\alpha_s(m_b=4.9\ \text{GeV}/c^2)=0.195\pm 0.002\,.$$

The errors given above are experimental only. The theoretical errors are unknown and may be large.

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[5] After visual inspection, events with five or six detected charged tracks are also included if a charged track interacts in the barrel calorimeter producing a hadronic shower, which gives one or two extra reconstructed charged tracks in the drift chamber. This effect is not modeled by our Monte Carlo calculation, and increases the data sample by 1%.

[6] The combined efficiencies for tracking and lepton identification within the selected solid angle region are 0.94 in period A and 0.89 in period B for a muon, and 0.96 for an electron. The probability of a nonlepton being identified as a lepton is between 2% (electron) and 4% (muon). The probability of dilepton misidentification is therefore at 0.1% level. In addition, considering the physics processes of J/ψ decay with two high momentum tracks leads to the dilepton misidentification probability much smaller than the above.

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[11] The following sets of Monte Carlo events were generated: $\psi(2S)\to\pi^+\pi^-J/\psi$, with $J/\psi\to$ all neutral, $J/\psi\to l^+l^-$, $J/\psi\to 2\pi^+2\pi^-$, $J/\psi\to 2\pi^+2\pi^-\pi^0$, $J/\psi\to 2\pi^+2\pi^-3\pi^0$, $J/\psi\to 3\pi^+3\pi^-$, and $J/\psi\to 3\pi^+3\pi^-\pi^0$. The efficiencies for different processes with the same charged-track multiplicity are approximately equal (within their statistical uncertainties).

[12] The method of using the barrel calorimeter for muon identification contains more background. Hence in this analysis the J/ψ signal shape used to determine the final number of events is obtained by fitting the dimuon invariant mass spectrum using the events which contain muon chamber hits.

[13] This result is consistent with, but is 4 times more precise than, the previous measurement of this branching fraction, $(6.9\pm 0.9)\%$, by A. Boyarski *et al.*, Phys. Rev. Lett. **34**, 1357 (1975).

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[15] In these calculations, we have updated the branching fractions used in Ref. [2] to the current values given by the Particle Data Group (Ref. [14]); for the leptonic decay branching fractions of the J/ψ, the measurement presented here is used. From the total widths we obtain $\Gamma(J/\psi\to ggg)=(0.661\pm 0.028)\Gamma_{\rm total}$, $\Gamma(\Upsilon(1S)\to ggg)=(0.805\pm 0.010)\Gamma_{\rm total}$. The fit gives $\mathcal{A}=-3.2\pm 0.1$, where we use $v^2/c^2=0.24$ and 0.073 for the charmonium and upsilon systems, respectively (see Ref. [2]).