Total Cross Section for Hadron Production by Electron-Positron Annihilation between 2.4 and 5.0 GeV Center-of-Mass Energy*

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The total cross section for hadron production by e^+e^- annihilation has been measured at center-of-mass energies between 2.4 and 5.0 GeV. Aside from the very narrow resonances $\psi(3105)$ and $\psi(3695)$, the cross section varies between 32 and 17 nb over this region with structure in the vicinity of 4.1 GeV.

We present measurements of the total cross section σ_T for hadron production by e^+e^- annihilation. Data were taken at 18 center-of-mass (c.m.) energies between 2.4 and 5.0 GeV. These explorations, which contributed to the discovery of very narrow resonances in σ_T,[1] show further structure on a broader energy scale.

The experiment, performed at the Stanford Linear Accelerator Center (SLAC) electron-positron colliding beam facility, SPEAR,[2] used a solenoidal magnetic spectrometer to detect e^+e^- interaction. The properties of the SLAC/Lawrence Berkeley Laboratory magnetic detector and trigger requirements have been described previously.[3] Hadronic final states[4] were separated from e^+e^- and $\mu^+\mu^-$ final states by selecting events with ≥ 3 charged particles detected, unless two of the tracks were collinear within 10° and had large shower-counter pulse height (consistent with electrons). Events with only two charged tracks were also classified hadronic if the tracks were acoplanar by more than 20°, and had small shower-counter pulse height (not electrons) and momenta ≥ 0.3 GeV/c. These two-prong events constitute between 12% and 18% of the event sample.

The efficiency for hadrons to set the trigger system was determined from events with ≥ 3 charged particles. This efficiency is momentum dependent; it rises from 20% at 175 MeV/c to 80% at 450 MeV/c, then continues to rise slowly to 95% as the momentum increases.

Studies of radial vertex distributions and visual scanning of several thousand events showed that failures of the tracking to find an event vertex within a 4-cm-radius cut lead to event losses which average 11% and do not favor any particular multiplicity or energy. The data were corrected for these losses.

The background due to beam-gas interactions was determined from longitudinal distributions of reconstructed event vertices. Runs taken with single beams have a uniform longitudinal distribution; colliding-beam runs show, in addition, a peak corresponding to the overlap region of the beams. The beam-gas background subtraction was $< 8\%$ at all energies.

The contamination from photon-photon processes[5] was estimated using small-angle (25 mrad) counters in coincidence with the detector to tag one or both of the forward-angle electrons and positrons characteristic of these processes. The measured contamination of ≥ 3-prong hadron events (corrected for tagging efficiency) is $(2\pm 2)\%$ at 4.8 GeV where the effect is expected to be largest. The tagging rate with two detected prongs is consistent with that calculated[6] for the electrodynamic processes $e^+e^- \to e^+e^-e^+e^-$, $e^+e^- \to e^+e^-\mu^+\mu^-$. To correct for that contamination, the number of two-prong events was reduced by an amount ranging from 8% at the highest energy to 3% at the lowest. We estimate that less than 6% of the total hadron yield after corrections can be attributed to these photon-photon processes.

The efficiency for detecting multihadron final states was calculated in two steps. First, a computer simulation of the detector, incorporating all known inefficiencies, was combined with a model of hadronic states to compute the detection efficiency as a function of the number of charged particles in the final state. These efficiencies enter into an overdetermined set of simultaneous equations which relate true and observed charged-particle multiplicity distributions. The second step was to solve these equations for the true multiplicity distribution by a maximum-likelihood method. The ratio of the number of events observed to that expected from the true distribution is the average detection efficiency $\bar{\epsilon}$. With this method, the form of the charged-particle multiplicity distribution in the model does not directly enter into the determination of $\bar{\epsilon}$. Values for $\bar{\epsilon}$ and the true mean charged multiplicity as determined by this procedure are given in Table I. The errors on $\bar{\epsilon}$ and the mean multiplicity are statistical only.

The sensitivity of $\bar{\epsilon}$ to the choice of the model of multihadron production was checked by comparing three different models. In two models, angular and momentum distributions of particles were given by Lorentz-invariant phase space. The third was a two-jet model where the jet axis had a $1+\cos^2\theta$ or $\sin^2\theta$ angular distribution and particles decayed from each jet with transverse momentum spectra as observed in strong interactions. One phase-space model and the jet model assumed only pion production; the other phase-space model allowed for the production of kaons, etas, and nucleons in addition to pions. Values of $\bar{\epsilon}$ determined with these very different models agree to $\pm 5\%$.

Large-angle Bhabha scattering ($e^+e^- \to e^+e^-$) events were used to normalize the data. Procedures for selecting events and computing the integrated luminosity are discussed in Ref. 3. Integrated luminosities are presented in Table I.

Radiative corrections[7] were applied by first subtracting the radiative tails of the two known ψ resonances[1] and then computing corrections due to the nonresonant cross section using the tail-subtracted cross section as input. These corrections range from -6% to $+5\%$. The net radiative corrections, expressed as the ratio of measured cross sections to corrected ones, are given in the table.

Final values of σ_T are given in the table and Fig. 1(a). The quoted errors include statistical errors to which an 8% systematic uncertainty was added in quadrature. This systematic error is an estimate of the point-to-point fluctuations

TABLE I. Table of experimental quantities relating to the measurement of the total hadronic cross section for the center-of-mass energies covered in this experiment.

Center-of-Mass Energy $E_{c.m.}$ (GeV)	Integrated Luminosity L $(nb)^{-1}$	Average Detection Efficiency ϵ	Mean Charged Multiplicity $\langle n_{ch}\rangle$	Net Radiative Correction σ_{meas}/σ_T	Total Cross Section σ_T (nb)
2.4	26.1	0.40 ± 0.02	3.31 ± 0.12	1.02	31.8 ± 3.6
2.6	14.1	0.37 ± 0.03	3.18 ± 0.15	1.02	32.5 ± 4.4
2.8	14.9	0.38 ± 0.03	3.37 ± 0.18	1.02	29.4 ± 4.1
3.0	152.0	0.43 ± 0.01	3.55 ± 0.04	1.02	23.3 ± 2.0
3.1	16.7	0.40 ± 0.04	3.51 ± 0.21	1.02	22.5 ± 3.4
3.2	50.8	0.48 ± 0.02	3.89 ± 0.12	1.29	21.4 ± 2.3
3.3	22.7	0.47 ± 0.03	3.84 ± 0.19	1.17	18.9 ± 2.6
3.4	25.4	0.51 ± 0.03	3.93 ± 0.19	1.12	18.7 ± 2.4
3.6	33.4	0.52 ± 0.03	4.00 ± 0.17	1.07	19.1 ± 2.2
3.8	421.9	0.50 ± 0.01	3.87 ± 0.05	1.21	19.7 ± 1.7
4.0	18.3	0.52 ± 0.04	3.90 ± 0.20	1.03	24.5 ± 3.3
4.1	26.5	0.50 ± 0.03	4.04 ± 0.17	0.98	31.8 ± 3.6
4.2	70.5	0.51 ± 0.02	4.00 ± 0.10	1.02	28.1 ± 2.7
4.3	31.3	0.50 ± 0.03	4.02 ± 0.18	1.06	23.6 ± 2.8
4.4	21.3	0.58 ± 0.04	4.40 ± 0.24	1.08	19.6 ± 2.5
4.6	38.7	0.63 ± 0.04	4.62 ± 0.23	1.08	15.3 ± 1.9
4.8	787.2	0.58 ± 0.01	4.31 ± 0.04	1.05	18.2 ± 1.5
5.0	198.0	0.57 ± 0.02	4.32 ± 0.09	1.04	17.7 ± 1.5

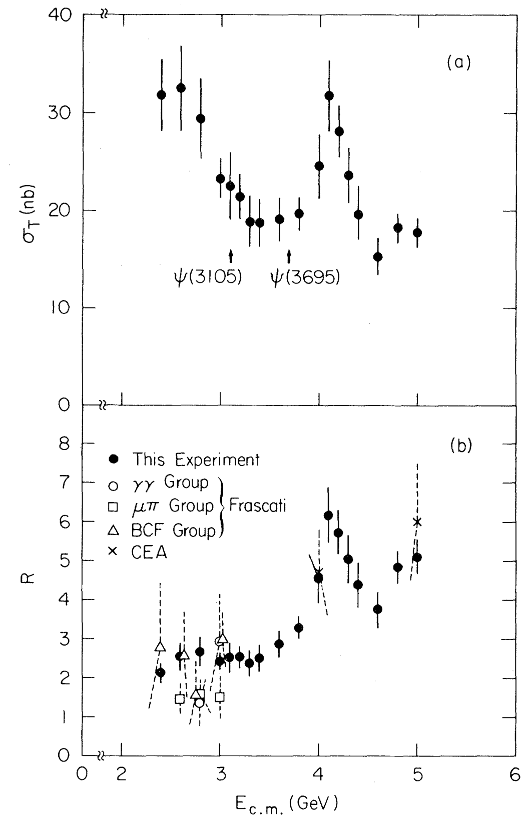

FIG. 1. (a) Total hadronic cross section σ_T versus center-of-mass energy from this experiment. The positions of the narrow ψ resonances (Ref. 1) are indicated; their cross sections and radiative tails are not included in σ_T. (b) Ratio R of σ_T to the theoretical muon pair production cross section versus $E_{c.m.}$. Also shown are previous results in the same energy region from Refs. 8 and 9.

which arise from errors in background subtraction, radial-cut corrections, detection efficiency, and radiative corrections. It is consistent with the reproducibility of measurements taken under different operating conditions of the detector or separated by long periods of time.

A further, smooth variation in σ_T, as large as 15% from lowest energy to highest, could arise from systematic errors in the energy dependence of $\bar{\epsilon}$. To this must be added a 10% uncertainty in absolute normalization.

Aside from the narrow resonances indicated in Fig. 1(a), the cross section falls smoothly with c.m. energy from 2.4 to 3.8 GeV, where it rises sharply, peaking near 4.1 GeV before falling again. The radiative corrections which account for the tails of the ψ resonances (see table) make the 4.1-GeV peak more pronounced. In Fig. 1(b), we present the ratio, R, of σ_T to the theoretical total cross section for production of muon pairs, together with earlier results.[8,9] R is approximately constant from 2.4 to 3.8 GeV, rises between 3.8 and 4.1 GeV, and at 5 GeV has a value about twice that of the low-energy "plateau." The structure shown in Fig. 1 suggests either new thresholds in the 4-GeV region or a broad resonance in σ_T centered at 4.1 GeV, or both.

While the present uncertainties in σ_T do not permit us to distinguish between these possibilities, we can estimate parameters describing this structure. *Assuming* it to be a single resonance above an 18-nb background, we find a peak centered at 4.15 GeV, an area of about 5500 nb MeV, and a total width of 250–300 MeV. Further, assuming the resonance to have spin 1 (the one-photon state), we find a partial width to electrons of roughly 4 keV. The partial width to electrons is comparable with those of the ψ(3105) and ψ(3695) (approximately 5 and 2 keV, respectively[10]), while the total width is very much greater. No enhancement in the cross section for lepton pairs is observed near 4.1 GeV, nor is one expected because of the small branching ratio to leptons that this resonance would have.

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[4]σ_T presented here excludes all-neutral final states because of trigger requirements. The hadron nature of the particles can only be established in certain kinematic regions. K's and p's are unambiguously identified through time of flight below 600 MeV/c. Significant lepton contamination at intermediate momenta (0.1–1.0 GeV/c) cannot be ruled out.

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Electron-Positron Annihilation at and above the Threshold for Production of Charmed Hadrons

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Charmed-quark models of the new narrow resonances at 3.1 and 3.7 GeV suggest that a virtual S state lies slightly above the charmed-hadron threshold. This state causes a large enhancement of $R=\sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ just above the threshold, followed by a dip and several broad but smaller enhancements at higher energy. Estimates of this intriguing structure in R are presented.

It has been proposed that the new narrow resonances[1] are S-wave bound states of heavy charmed quarks.[2,3] This physical picture and the idea that strong interactions are described by an asymptotically free gauge theory provide a good first-order understanding of some of the striking properties of these states. Pursuing this suggestion further several authors[4] have constructed simple models of these bound states in order to understand their structure and decay modes in more detail.

These investigations have dealt most vigorously with either the new resonances themselves or the approach of the annihilation cross section to the asymptotic region. However, between these two regions lies the threshold for the production of charmed hadrons. This kinematic region and the behavior of R there is the subject of this note. On the basis of the ideas mentioned in the first paragraph we suggest that R has considerable interesting structure in the energy region $E=3.9$–5.5 GeV. Calculations done in simple models described below suggest that just above threshold there is a *sharp enhancement* in R followed by a dip and *several smaller broad enhancements.* These calculations strengthen a conjecture of Eichten *et al.*[4] that the presence of a 3S state above threshold should be visible in R. The height and width of the enhancement just above threshold (at 4.0 GeV, say) are about 6.2 and 300–400 MeV, respectively. The position of the first dip above threshold occurs at about 4.5 GeV. The height of the second enhanced region is estimated at 4.5. A second dip occurs at 5.5 GeV and a smaller enhancement follows [see Figs. 1(a) and 1(b)].

First we discuss the theory behind these remarks. Consider a simple approach to bound states of heavy charmed quarks (let c denote the charmed quark) in a theory containing ordinary quarks and Yang-Mills gauge fields. Under certain circumstances the interaction between a c and a $\bar{c}$ can be described by a nonrelativistic potential $V(r)$. These conditions are similar to those which determine the validity of the Born-Oppenheimer approximation[5] in molecular physics. In particular, if the c quarks are sufficiently heavy and slow moving, then the ordinary quark and vector fields can be treated in an adiabatic approximation.[5] To define the adiabatic approximation we first consider a fictitious problem in which the degrees of freedom are the Yang-Mills field $A_{\alpha,\mu}$, the ordinary, light-quark fields ψ, and a pair of static sources of the Yang-Mills field at positions r_1 and r_2. The static sources consist of