Quantum Numbers and Decay Widths of the $\psi(3684)$*

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Cross sections for $e^+e^- \to$ hadrons, e^+e^-, and $\mu^+\mu^-$ near 3684 MeV are presented. The $\psi(3684)$ resonance is established as having the assignment $J^{PC}=1^{--}$. The mass is 3684 $\pm$ 5 MeV. The partial width for decay to electrons is $\Gamma_e = 2.1 \pm 0.3$ keV and the total width is $\Gamma = 228 \pm 56$ keV.

Extensive data on the production of hadrons, μ pairs, and e pairs by e^+e^- annihilation have been recorded by the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory solenoidal detector at SPEAR at c.m. energies near the $\psi(3684)$ resonance.[1] These measurements are used to determine the spin, the parity, and the charge conjugation of the $\psi(3684)$ as well as its mass, its total width, and the partial decay widths to leptons and to hadrons. It having been established that the $\psi(3095)$, like the photon, is a $J^{PC}=1^{--}$ state,[2] it is of particular interest to find out whether the $\psi(3684)$ is a similar state.

The data acquisition, the event selection, and the determination of the cross sections have been described previously.[3] There is, however, a difference in the selection of lepton pairs. A study of the momentum spectra for collinear lepton pairs reveals two separated peaks, one corresponding to pairs produced at full energy, i.e., direct $\mu^+\mu^-$ or e^+e^- production by quantum electrodynamics (QED) plus the decays $\psi(3684) \to \mu^+\mu^-$ and e^+e^-, and a second peak at lower momenta due to the process[4]

$$\psi(3684) \to \psi(3095) + \text{neutrals}$$
$$\hookrightarrow \mu^+\mu^- \text{ or } e^+e^-.$$

Whereas the $\mu^+\mu^-$ pairs from the cascade decay can be eliminated by a cut on the invariant mass at 3.316 GeV with a loss of 4% of the direct decays, the same cut applied to the e^+e^- pairs removes a large fraction of the data because of radiative effects. In order to reduce these losses to a level of 5% and to keep the contamination below 0.5%, events with at least one momentum above 1.7 GeV are counted as direct decays. These cuts are illustrated in Fig. 1.

The cross sections for the three measured processes are presented in Figs. 2(a)–2(c). In contrast to the hadron data, the lepton data have

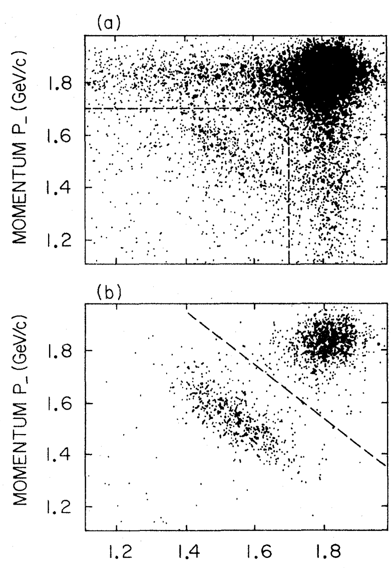

FIG. 1. Momentum of the negative lepton versus the momentum of the positive lepton for collinear (within 10°) two-prong events. e pairs (a) are separated from μ pairs (b) using shower-counter pulse-height data. The cuts to select direct decays are marked by the dashed lines.

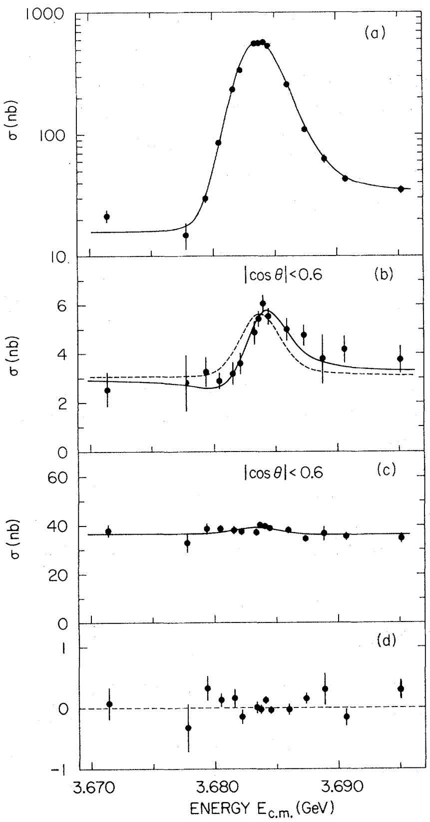

FIG. 2. Cross sections for (a) $e^+e^-\rightarrow$hadrons, (b) $e^+e^-\rightarrow\mu^+\mu^-$, and (c) $e^+e^-\rightarrow e^+e^-$ versus center-of-mass energy. The solid curves represent the result of the fit to the data; the dashed line in (b) represents no interference. (d) The front-back asymmetry for the μ^+ in $e^+e^-\rightarrow\mu^+\mu^-$.

not been corrected for the loss of events with $|\cos\theta|>0.6$, where θ is the angle between the outgoing positive lepton and the incident positron beam. The most prominent features of the data are the copious production of hadrons and the width of the distribution, which is compatible with the energy resolution of the machine. Whereas the μ-pair production is enhanced by a factor of 2 by the resonance, the e-pair rates are dominated by t-channel Bhabha scattering and thus provide the overall luminosity calbration.

In order to obtain the exact mass m, and the partial widths for decay into electrons, muons, and hadrons, Γ_e, Γ_μ, and Γ_h, respectively, the three data sets are fitted simultaneously. The fitting procedure is identical to that applied to determine the properties of the $\psi(3095)$,[2] though, because of the small branching fraction into leptons, μ-e universality has to be used, i.e., $\Gamma_e=\Gamma_\mu$. The total width is defined as $\Gamma=\Gamma_e+\Gamma_\mu+\Gamma_h$,

TABLE I. Properties of $\psi(3684)$.

m	3.684 ± 0.005 GeV
J^{PC}	1^{--}
$\Gamma_e(=\Gamma_\mu)$	2.1 ± 0.3 keV
Γ_h	224 ± 56 keV
Γ	228 ± 56 keV
Γ_e/Γ	0.0093 ± 0.0016
Γ_h/Γ	0.981 ± 0.003
$\Gamma_{\gamma h}/\Gamma$	0.029 ± 0.004

thus assuming no unobserved decay modes. The fit takes a Breit-Wigner amplitude and adds a nonresonant direct-channel amplitude. It is assumed (and will be justified later) that the $\psi(3684)$, like the photon, is a $J^{PC}=1^{--}$ state. Consequently the leptonic decays have an angular distribution of $1+\cos^2\theta$ and there is maximum interference between the s-channel QED amplitude and the Breit-Wigner amplitude. These theoretical cross sections are folded over the energy distribution of the colliding beams, which itself is treated as an analytic fold of a Gaussian resolution function and radiative energy losses in the initial e^+e^- state. Radiative effects like vertex corrections and vacuum polarization, as well as final-state radiation of the leptons, are included.[5] The variation of the energy resolution as a function of the beam current is taken into account.[6]

The fit varies the following parameters: The mass m, the partial widths Γ_h and $\Gamma_e\,(=\Gamma_\mu)$, the energy spread of the machine, an overall luminosity normalization constant, and the nonresonant hadronic cross section. The point-to-point errors include a $\pm 2\%$ systematic uncertainty added in quadrature to the statistical error. A ± 50 keV uncertainty in the c.m. energy setting is taken into account. The results of the fit are given in Table I. The errors on the decay widths are dominated by an overall uncertainty in the hadron detection efficiency of $\pm 15\%$. The difference between the masses of the $\psi(3095)$ and of the $\psi(3684)$ is 588.7 ± 0.8 MeV. The assumption that leptons couple to the $\psi(3684)$ only via an intermediate photon implies the existence of the decay $\psi(3684)\rightarrow\gamma\rightarrow$ hadrons with a branching fraction

$$\Gamma_{\gamma h}/\Gamma=R\Gamma_e/\Gamma=0.029\pm 0.004,$$

which corresponds to a width of 6.7 keV.

The spin, parity, and charge conjugation of the $\psi(3684)$ resonance are established by study of the μ-pair decay using the same arguments as in Ref. 2. The data in Fig. 2(b) are compared to

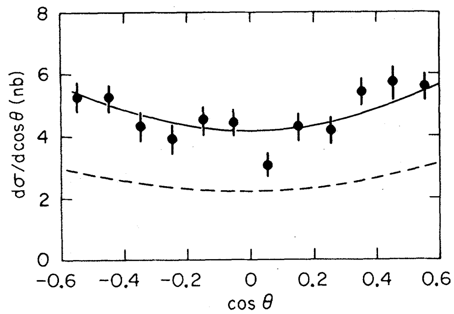

FIG. 3. Angular distribution of μ^+ in $e^+e^- \to \mu^+\mu^-$ in the center of the $\psi(3684)$ peak. The solid curve is the fit assuming $f(\theta) = 1 + \cos^2\theta$; the dashed curve is the QED contribution.

the fitted curve having maximum interference, i.e., a pure $J^{PC} = 1^{--}$ state, as well as to a fit without interference, e.g., $J = 0$. The former yields $\chi^2 = 37$ for 39 degrees of freedom, while no interference yields $\chi^2 = 61$. The data give a preference for the 1^{--} assignment by 4.9 standard deviations. Thus, one concludes that the $\psi(3684)$ shares the quantum numbers of the photon.

Moreover, the angular distributions of the μ pairs support this assignment. The front-back asymmetry measured as a function of energy is given in Fig. 2(d). The data are consistent with zero asymmetry which argues against $\psi(3684)$ being a degenerate mixture of states of opposite P and C. The angular distribution at the center of the resonance as shown in Fig. 3 confirms that the $\psi(3684)$ is a $J = 1$ state.

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Kinematic Constraints on the Production of Magnetic Monopoles*

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A lower limit for the lab energy of a magnetic monopole produced from a stationary target is derived and used to study implications of the data of Price *et al.*

The exciting evidence of Price *et al.*[1] for the existence of a magnetic monopole raises immediate questions about the means of production. Crucial to such considerations are the mass and speed of the monopole. I have found that there is a rigorous lower limit to the lab energy of a monopole immediately following its production from a stationary target. This limit can be used to virtually rule out scenarios involving production in the atmosphere immediately above the detectors.

Consider the production of a monopole and antimonopole pair via the collision of a projectile m_1 with a target m_2 at rest in the lab. At the threshold for the reaction, a monopole with mass m_3 has the velocity of the c.m. (zero-momentum) frame, so that to get a speed in the lab less than $\beta_{\text{c.m.}}$ it has to be ejected backwards in the c.m. frame. To get the minimum energy in the lab, the recoiling monopole would need to have its maximum energy in the c.m. frame. This situation can be achieved if all of the other particles produced in the collision are ejected as a "quasiparticle" of mass m_4 in the forward direction. With the problem reduced to the relativistic kinematics of the two-body reaction $m_1 + m_2 \to m_3 + m_4$, the computation is straightforward.

The most physically illuminating demonstration of the limit comes from using $\beta_{3,\max}'$ (speed of the monopole in the c.m. frame) and $\beta_{\text{c.m.}}$ to