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DISCLAIMER

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OBSERVATION OF A RESONANCE IN e^+e^- ANNIHILATION JUST ABOVE CHARM THRESHOLD*

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ABSTRACT

We observe a resonance in the total cross section for hadron production in e^+e^- annihilation at a mass of 3772 ± 6 MeV/c^2 having a total width of 28 ± 5 MeV/c^2 and a partial width to electron pairs of 370 ± 90 eV/c^2.

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Previously detailed studies of the total cross section for hadron production (σ_T) by e^+e^- annihilation have concentrated on center-of-mass energies ($E_{c.m.}$) above 3.9 GeV.[1-3] In this Letter we report high statistics measurements of σ_T between the $\psi(3684)(\equiv\psi')$ and 3.9 GeV. We observe a resonance near 3.77 GeV, just above the threshold for the production of charmed particles.

The data were collected with the SLAC-LBL magnetic detector at SPEAR.[4-6] In order to maintain consistency with previous measurements, the event selection criteria and experimental corrections are substantially the same as those used in Ref. 1. Hadronic events are selected as events with two or more detected charged tracks which form a vertex within a cylindrically shaped fiducial volume 22 cm long and 4 cm in radius centered about the interaction region. If only two oppositely charged particles are detected, they are required to be acoplanar with the incident beams by at least 20^o, each to have a momentum greater than 300 MeV/c, and to have at least one particle not identified as an electron. Cosmic rays are rejected by time-of-flight measurements. Backgrounds from beam-gas interactions ($\sim$2%) are subtracted using events detected beyond the ends of the fiducial cylinder. A small correction (<1%) is also made for contamination from two-photon processes.[7,8] The luminosity is determined from measurements of large angle e^+e^- scattering in the magnetic detector.[4,7]

To correct for the efficiency of the apparatus to detect hadronic events (ε), we used the same smooth function of energy which was used in Ref. 1. It is based on an unfolding procedure in which the produced charged-particle multiplicity distribution is deduced from the observed distribution and on Monte Carlo calculations which determine the detector response to each produced multiplicity.[7,9] The use of a smooth function for ε is justified only if the observed mean multiplicity and observed mean momentum vary smoothly with energy over the $E_{c.m.}$ region of interest. Figure 1 shows the variation of these quantitities with $E_{c.m.}$. There does not appear to be any significant structure with the exception that the observed multiplicity is higher in the region where the ψ' radiative tail is important. This is caused by the relatively high multiplicity in ψ' decays. As a consequence of using a smooth function for ε, we measure a slightly larger magnitude for the ψ' tail than if we used a locally varying ε; however, since we subtract the ψ' tail experimentally using the same technique, as will be discussed below, no error is introduced in the determination of radiatively corrected cross sections. The values of ε used vary from 0.51 at $E_{c.m.} = 3.7$ GeV to 0.53 at $E_{c.m.} = 3.9$ GeV. There is, in addition, an experimentally measured correction of about 9% for events which are lost because they appear to form a vertex at a radial distance of greater than 4 cm from the line of the incident beams.

Rather than displaying σ_T directly, we follow the usual practice of plotting the ratio R of σ_T to the theoretical cross section for production of muon pairs. Figure 2a shows R before radiative corrections. The error bars represent only the statistical uncertainties. There is an additional overall systematic uncertainty of 15%, arising largely from the uncertainty in ε. There is clearly an enhancement near 3.77 GeV, but it is partially obscured by the ψ' radiative tail.

Corrections for radiative effects in the initial state[10] can be divided into four parts: the corrections due to the continuum, the tail of the ψ(3095), the tail of the ψ', and the resonance at 3.77 GeV. At 3.77 GeV these corrections are -5%, -2%, -13%, and +9%, respectively. Since the tail of the ψ' is relatively large in the $E_{c.m.}$ region covered here, we determined

its size experimentally by performing a two parameter fit to the data in the $E_{c.m.}$ region from 3.692 to 3.730 GeV. The two parameters were the magnitude of the ψ' tail and the non-resonant value of R.
The shape of the ψ' tail was given by the standard formula.[10]
The radiatively corrected values of R are shown in Fig. 2b and in Fig. 3 along with an additional measurement at 3.6 GeV and the results of previous measurments in the same detector.

Although neither the observed mean multiplicity nor the mean momentum varies significantly in the region around the 3.77 GeV peak, preliminary evidence indicates that there is copious production of $D\bar{D}$ pairs at this peak. For this reason it is appropriate to fit it to a Breit-Wigner,

$$R = \frac{\sigma_T}{\sigma_{\mu\mu}} = \frac{3\pi}{\sigma_{\mu\mu} m^2} \frac{\Gamma_{ee}\Gamma(E)}{(E_{c.m.} - m)^2 + \Gamma^2(E)/4} \qquad (1)$$

where m is the mass of the resonance, Γ_{ee} is the partial width to electron pairs, and $\Gamma(E)$ is the total width whose energy dependence is proportional to

$$\Gamma(E) \propto \frac{p_o^3}{1 + (rp_o)^2} + \frac{p_+^3}{1 + (rp_+)^2} \quad . \qquad (2)$$

Here p_o and p_+ represent the momenta of a D^o and a D^+ respectively, from D pair production, and r represents an interaction radius.[11] Although the data are fit better with energy independent widths, we can obtain acceptable fits for all values of r greater than 1 fm. A fit for $r = 3$ fm is shown in Fig. 2b. The form of the background was found not to be critical, and for this fit was arbitrarily taken to be a constant plus a constant times $(p_o^3 + p_+^3)$. The fit has a χ^2 of 16.9 for 15 degrees of freedom. The parameters of this fit[12] are given in Table I along with the previously determined parameters of the other isolated ψ resonances.[1,13,14]

The parameters of the $\psi(3772)$ are in striking agreement with these predicted by Eichten et al.[15] for the $^3D_1$ state of charmonium. In a calculation which was updated to include the measured D^o mass, Lane and Eichten[16] correctly predicted the mass and total width and underestimated the leptonic width by about a factor of two. In a nonrelativistic approximation, a D-state does not couple to e^+e^-. It can obtain a leptonic width, however, by mixing with an S-state. It is normally assumed that the $^3D_1$ mixes primarily with the 2^3S_1, which is identified with the ψ'. In the approximation in which only these two states mix, one can calculate from the data in Table I that the mixing angle is 23 ± 3^o.

Other explanations for the $\psi(3772)$, such as its being a four-quark state,[17] are conceivable, but are not required by the present data.

The rapid analysis of these results was made possible by the work of the previous users of the magnetic detector, many of whom are not members of the present collaboration. In particular, we are indebted to J. Siegrist and R.F. Schwitters for discussions on the measurement of total cross sections. We would also like to thank D.L. Scharre for discussions on radiative corrections. We are very grateful to K. Lane for emphasizing to us the theoretical prediction of a resonance in this region and to F.J. Gilman for useful discussions.

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12. The fit with an energy independent width and the same background form had a χ^2 of 10.6 for 15 degrees of freedom. It gave a mass of 3771 MeV/c^2, a total width of 31 MeV/c^2, and a leptonic width of 420 eV/c^2. The errors given in Table I take into account the uncertainty in the form of the fitting function.

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TABLE I

Resonance parameters for the isolated ψ resonances. Γ is the full width, Γ_{ee} is the partial width to electron pairs, and B_{ee} is the branching fraction to electron pairs.

State	Mass[a] (MeV/c^2)	Γ (MeV/c^2)	Γ_{ee} (keV/c^2)	B_{ee}
ψ(3095)[b]	3095 ± 4	0.069 ± 0.015	4.8 ± 0.6	0.069 ± 0.009
ψ(3684)[c]	3684 ± 5	0.228 ± 0.056	2.1 ± 0.3	$(9.3 \pm 1.6) \times 10^{-3}$
ψ(3772)	3772 ± 6	28 ± 5[d]	0.37 ± 0.09	$(1.3 \pm 0.2) \times 10^{-5}$
ψ(4414)[e]	4414 ± 7	33 ± 10	0.44 ± 0.14	$(1.3 \pm 0.3) \times 10^{-5}$

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[a] Errors include a 0.13% uncertainty in the absolute energy calibration of SPEAR. The mass difference between the ψ(3684) and ψ(3772) is 88 ± 3 MeV/c^2.

[b] Ref. 13.

[c] Ref. 14.

[d] Energy-dependent width evaluated at the mass of the resonance.

[e] Ref. 1.

FIGURE CAPTIONS

1. (a) Observed mean charged-particle multiplicity and (b) mean charged-particle momentum vs. $E_{c.m.}$.
2. R vs. $E_{c.m.}$ (a) before and (b) after corrections for radiative effects. The curve is a p-wave Breit-Wigner shape described in the text. The mass of the ψ' and the approximate positions of the thresholds for $D^o\overline{D^o}$ and $D^o\overline{D^{*o}}$ production are indicated.
3. Radiatively corrected values of R vs. $E_{c.m.}$. The closed circles are from this experiment, open squares are from Ref. 1, and the crossed point is from Ref. 7. The "3.8 GeV" point from Ref. 7 with $R = 3.28 \pm 0.28$ has been omitted because the exact energy at which it was taken is not known with sufficient accuracy to properly locate it on the high energy side of the $\psi(3772)$.

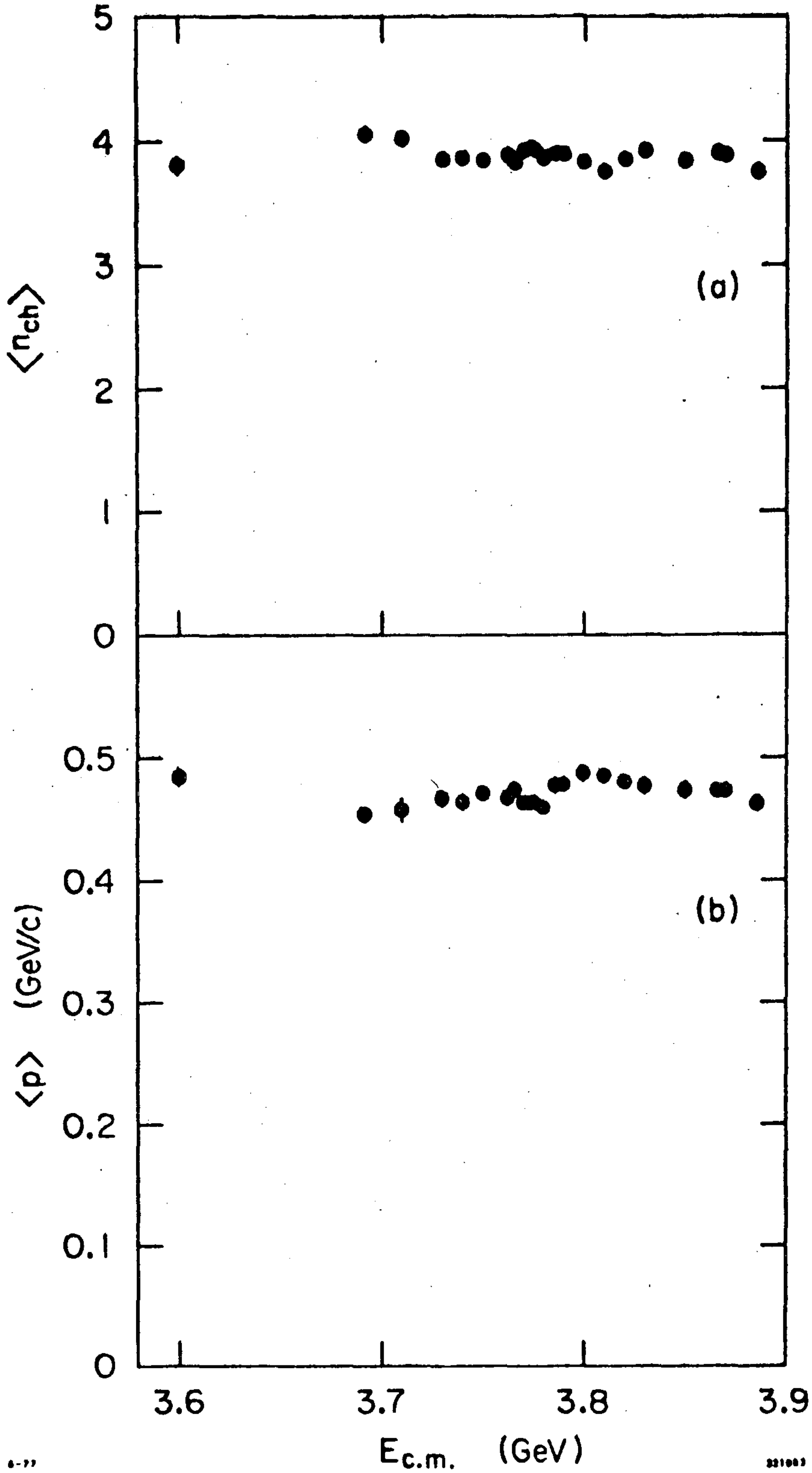

Fig. 1

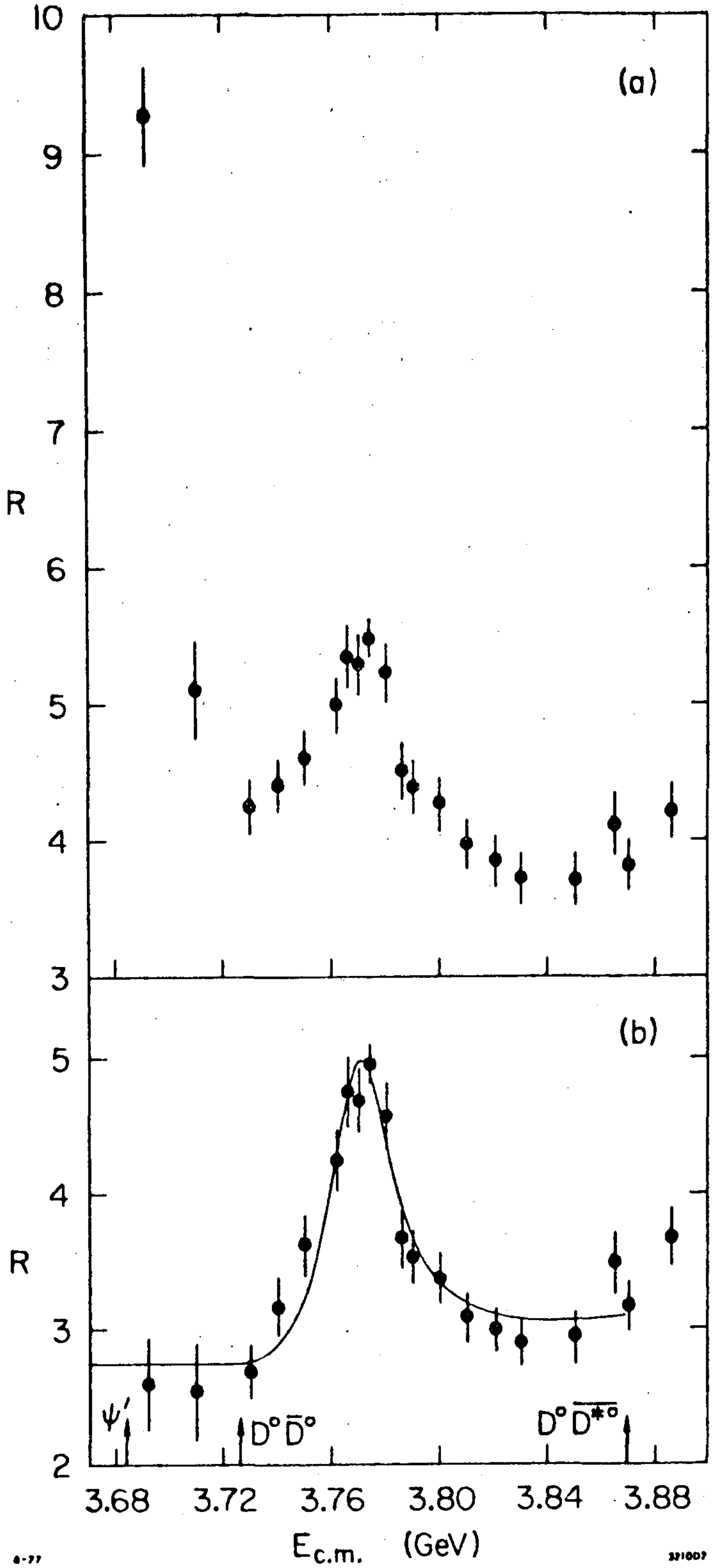

Fig. 2

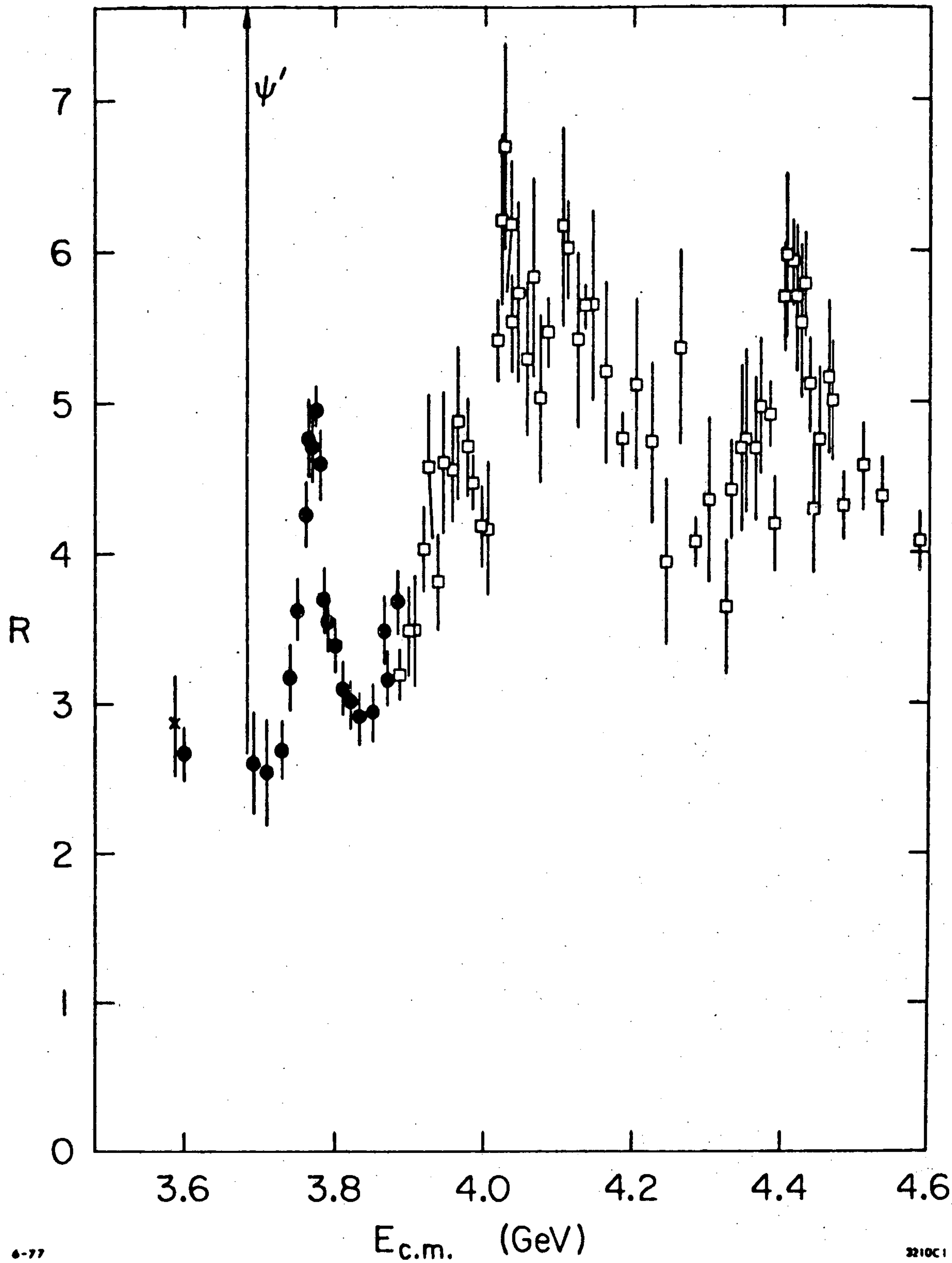

Fig. 3

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