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Observation of a Resonance at 4.4 GeV and Additional Structure near 4.1 GeV in e^+e^- Annihilation*

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We observe a resonancelike structure in the total cross section for hadron production by e^+e^- colliding beams at a mass of 4414 ± 7 MeV having a total width $\Gamma = 33 \pm 10$ MeV. From the area under this resonance, we deduce the partial width to electron pairs to be $\Gamma_{ee} = 440 \pm 140$ eV. Further structure of comparable width is present near 4.1 GeV.

In a previous Letter[1] we reported structure in the total cross section σ_T for hadron production by e^+e^- annihilation near the center-of-mass energy $E_{\text{c.m.}} = 4.15$ GeV. The width of that structure appeared to have a typical hadronic value of several hundred MeV, yet the area under it was comparable to the areas under the very narrow resonances $\psi(3095)$[2] and $\psi(3684)$.[3] We report here results from additional measurements of σ_T in the c.m. energy range 3.9 to 4.6 GeV. These data show strong evidence for a new state at 4414 ± 7 MeV having a total decay width of approximately

30 MeV and a partial width to lepton pairs only about 10% of that of the $\psi(3095)$. The new data also suggest that the broad 4.15-GeV peak noted in our previous Letter has substructure on a scale of 50 MeV or less.

This experiment was performed with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at the Stanford Linear Accelerator Center e^+e^- storage ring SPEAR. Operation of the detector, event selection criteria, and other aspects of the experiment relating to the measurement of σ_T are identical to those discussed in Ref. 1. Briefly, we select as hadrons those events where three or more charged tracks form a vertex within the luminous region of the beams, or where two prongs with momenta $p > 0.3$ GeV/c are present and, if oppositely charged, the two prongs are acoplanar with respect to the incident beam direction by at least 20°. We normalize to Bhabha-scattering ($e^+e^- \rightarrow e^+e^-$) events observed in the detector. Bhabha-scattering events are selected by collinearity ($\theta_c < 10°$), momentum ($p > \frac{1}{4}E_{\text{c.m.}}$), and shower-counter pulse-height criteria as discussed in Ref. 1 and by Augustin *et al.*[4] Cosmic rays are rejected by time-of-flight criteria.

Our basic measurement is the ratio of the number of hadron events to the number of Bhabha-scattering events. To obtain the more useful quantity R, the ratio of σ_T to the total cross section for muon-pair production, we correct the number of hadronic events by the average detection efficiency ϵ of the apparatus and assume the validity of quantum electrodynamics to relate the number of Bhabha-scattering events to the total number of muon pairs produced. In Ref. 1, ϵ was determined by an unfolding procedure where the actually produced hadron multiplicity distribution was derived from the observed multiplicity distribution and known properties of the detector. Here, where we are only interested in possible structure in R over a limited range of $E_{\text{c.m.}}$, a smooth function was fitted to the energy dependence of ϵ found in Ref. 1 and this was then used to determine R. As shown in Fig. 1, both the observed mean charged-particle multiplicity and momentum have a smooth energy dependence, justifying the use of the smoothed ϵ which varies between 0.53 at $E_{\text{c.m.}} = 3.90$ GeV and 0.57 at $E_{\text{c.m.}} = 4.60$ GeV.

The data were corrected for contamination from beam-gas interactions (< 5%) by normalizing to events with vertices outside the luminous region of the beams. Radiative tails of the narrow ψ resonances have been subtracted.

We estimate the systematic uncertainty in the absolute normalization of R to be ± 15%, arising mainly from uncertainties in ϵ. Point-to-point changes in R coming from instrumental effects are estimated to be less than 5%. Data spanning

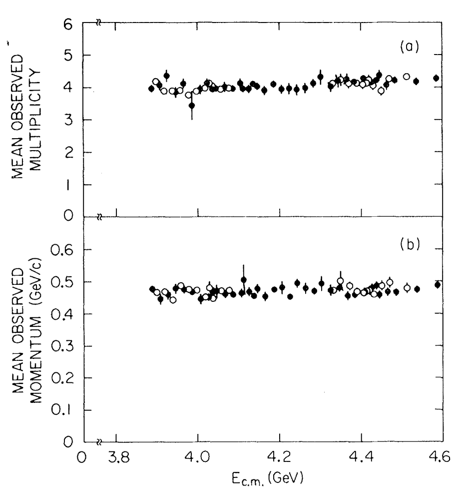

FIG. 1. (a) Observed mean charged-particle multiplicity versus $E_{\text{c.m.}}$. (b) Observed mean charged-particle momentum versus $E_{\text{c.m.}}$. The open and closed circles indicate data taken during different running periods separated by several months.

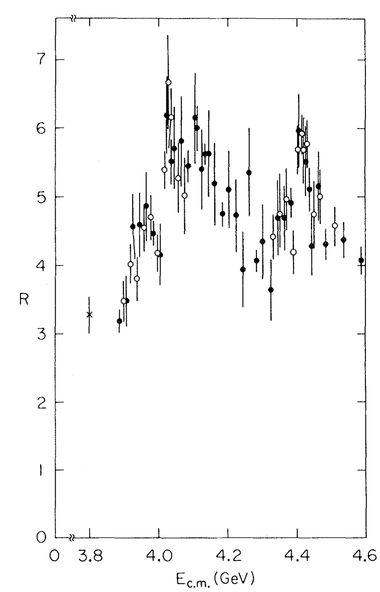

FIG. 2. Ratio R of hadronic cross section to muon-pair cross section versus $E_{\text{c.m.}}$ in the 4-GeV region. The open and closed circles refer to data separated by several months in time. The crossed point is taken from Ref. 1.

TABLE I. Resonance parameters for the $\psi(3095)$, $\psi(3684)$, and $\psi(4414)$. Γ is the full width, Γ_{ee} the partial width to electron pairs, and B_{ee} the branching ratio to electron pairs.

State	Mass (MeV)	Γ (MeV)	Γ_{ee} (keV)	B_{ee}
$\psi(3095)$[a]	3095 ± 4	0.069 ± 0.015	4.8 ± 0.6	0.069 ± 0.009
$\psi(3684)$[b]	3684 ± 5	0.228 ± 0.056	2.1 ± 0.3	0.0093 ± 0.0016
$\psi(4414)$	4414 ± 7	33 ± 10	0.44 ± 0.14	$(1.3 \pm 0.3) \times 10^{-5}$

[a]Ref. 2. [b]Ref. 3.

the entire energy range considered here and taken during different periods of time separated by several months are in excellent agreement where they overlap in energy as shown in Fig. 2. The ratio between the integrated luminosities derived from Bhabha-scattering events observed in the detector and events detected by small-angle ($\theta \approx 20$ mrad) counter telescopes was constant within statistical errors at all energies. Both the Bhabha-scattering and multihadron event samples were stable to the imposition of more stringent spark-chamber tracking criteria, thus verifying the stability of our tracking efficiency at all energies.

The data are presented in Fig. 2. Different symbols (open and closed circles) indicate data taken during different running periods separated by several months. The indicated errors are statistical only. Our previous measurement at $E_{\text{c.m.}} = 3.8$ GeV is also plotted. There is clear evidence for a peak in R near 4.4 GeV. Between 3.9 and 4.3 GeV, R has a broader peak with evidence for substructure on a scale of energy comparable to the peak at 4.4 GeV. Indeed, a separate peak at 3.95 GeV and a dip near 4.08 GeV are indicated by the data of Fig. 2. However, with the present data, we cannot say whether this substructure represents several independent resonances or an interference effect between two resonances.

We have fitted the cross section in the region 4.290 to 4.540 GeV with a Breit-Wigner resonance term plus a term linear in $E_{\text{c.m.}}$ to represent the nonresonant cross section. The fit assumed that the resonant and nonresonant contributions do not interfere and included the effects of radiative corrections[5] to the resonance line shape. Resonance parameters derived from the fit are summarized in Table I along with our previous[2,3] values for the $\psi(3095)$ and $\psi(3684)$. The data used in the fit and the resulting fit for the $\psi(4414)$ are given in Fig. 3. The χ^2 is 17.9 for 20 degrees of freedom. Under the assumption that this structure is a vector particle and that we observed the total production cross section, its decay width to e^+e^- pairs is $\Gamma_{ee} = 440 \pm 140$ eV, where we have included the uncertainty in the absolute detection efficiency in our estimate of the error.

Given their proximity in mass, it is natural to compare these new structures with the narrow ψ resonances. The magnitudes and widths of the 4-GeV structures are considerably different from those of the ψ particles; the $\psi(4414)$ has a full width over 100 times that of the $\psi(3684)$, yet its coupling to e^+e^- pairs, Γ_{ee}, is only $\frac{1}{5}$ of that of the $\psi(3684)$. The area under the broad 4.1-GeV peak is comparable to that under the $\psi(3684)$, but it may represent the sum of several states. If the $\psi(4414)$ is related to the narrow resonances, its much greater width may indicate that the selection rules responsible for the narrowness of the $\psi(3095)$ and $\psi(3684)$ may no longer be operative at 4 GeV. Several theoretical models[6] of the new particles have shown that structure in the 4-GeV region can arise from either new vector

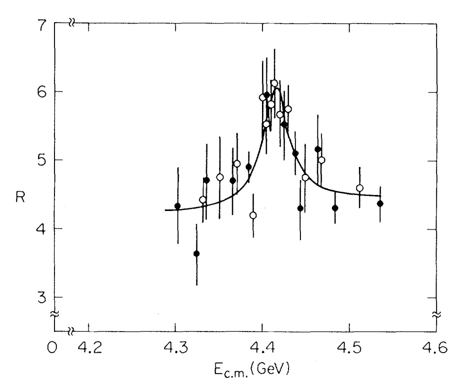

FIG. 3. Detailed plot of R versus $E_{\text{c.m.}}$ for data points used in the fit of the 4414-MeV resonance.

states or new production thresholds, or both.

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Observation of Two Strangeness-One Axial-Vector Mesons*

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We present a partial-wave analysis of the $K^{\pm}\pi^+\pi^-$ system in $K^{\pm}p \to K^{\pm}\pi^+\pi^-p$ at 13 GeV. Evidence is given for the existence of two $J^P = 1^+$ mesons: one at ~1300 MeV ($\Gamma \sim 200$ MeV) coupling principally to ρK and the other at ~1400 MeV ($\Gamma \sim 160$ MeV) coupling principally to $K^*\pi$.

An outstanding problem of meson spectroscopy is the lack of positive identification of the axial-vector mesons other than the B meson.[1,2] The quark model predicts two octets of such states, the A_1 octet with $J^{PC} = 1^{++}$ and the B octet with $J^{PC} = 1^{+-}$. In this paper evidence is given for the existence of two strange axial-vector mesons, Q_1 and Q_2, with masses of ~1300 and ~1400 MeV, respectively. The evidence comes from a three-body partial-wave analysis of data from a spectrometer experiment studying the reactions $K^{\pm}p \to K^{\pm}\pi^+\pi^-p$ at 13 GeV.

Past searches for Q mesons in these reactions have been hampered by both experimental and interpretive problems. Previous partial-wave analyses[3-5] of $K\pi\pi$ data have revealed no structure characteristic of resonance production, namely, comparatively narrow peaks in the mass spectrum accompanied by large phase variation. Statistics have limited these analyses to 100-MeV mass bins. The broad enhancements which have been observed in the 1^+ $K^*\pi$ system[3-5] may be qualitatively understood within the context of "Deck" models.[6]

The present experiment was performed at Stanford Linear Accelerator Center using 13-GeV rf-separated $K^{\pm}$ beams incident on a 1-m hydrogen target. The spectrometer[7] used to detect the $K\pi\pi$ system consisted of nine magnetostrictive readout wire spark chambers and a dipole magnet with a 17.6-kG-m field integral. The secondary particles were identified in a multicell pressurized Cherenkov counter oriented to detect preferentially the beam-charge K and π. The counter was filled with Freon 12 at 1.65 atm and gave K/π identification between 2.6 and 9.25 GeV. The data sample includes events in which the beam-charge K and π were identified (~50%) together with events with only the K or the π positively identified (~25% each). Events for the present analysis are selected by requiring that the missing mass recoiling against the $K\pi\pi$ system lie in the range $0.74 < MM < 1.10$ GeV. The background within this interval is less than 5%. In the $K\pi\pi$ mass interval $1.0 < m(K\pi\pi) < 1.6$ GeV, there are 72 000 $K^+\pi^+\pi^-$ events and 56 000 $K^-\pi^+\pi^-$ events. For the much larger sample of $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ beam decays, used for apparatus efficiency studies and relative normalization checks, the 3π invariant-mass resolution is 10 MeV full width at half-maximum.

At a given $K\pi\pi$ mass m and momentum transfer t (or $t' = t - t_{\min}$), the $K\pi\pi$ system is defined by five variables, $\omega = (\alpha, \beta, \gamma, s_{K\pi}, s_{\pi\pi})$. The Euler angles α, β, and γ describe the orientation of the $K\pi\pi$ decay plane coordinate system with respect