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# THE NEW PARTICLES\*

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# ABSTRACT

The properties of the new particles are reviewed in the context of the behavior of electron-positron annihilation into hadrons. The phenomenology of  $\psi(3100)$  and  $\psi'(3700)$  decays is discussed in some detail with emphasis on what the decays allow us to infer about the resonances, and on the difficulties which the observation and, more critically, the nonobservation of certain modes causes possible theories.

## INTRODUCTION

On November 17, 1974, many newspapers carried an Associated Press story which began:

"STANFORD, CALIF. (AP)—Stanford University announced Saturday the discovery of a new kind of elementary particle a basic constituent of all matter—with novel and not yet understood properties.

"The announcement said the same discovery was made independently at opposite ends of the country by scientific teams at the Stanford Linear Accelerator Center and the Brookhaven National Laboratory in New York. The announcement was made simultaneously by both laboratories.

"But the scientists said, 'The discovery is abstract. We don't know what it means.'"

It is now almost exactly eight months since the discovery<sup>1</sup> of the first of the new particles,  $\psi(3100)$ , and while the discovery may not be so abstract, we certainly are still searching for its full meaning.

As we know, a second narrow resonance  $\psi'(3700)$  was found<sup>2</sup> less than two weeks later. In data published<sup>3</sup> at the beginning of this year, there is evidence for another, much broader state  $\psi''(4100)$ , together with a step in R, the ratio of the total cross section for electron-positron annihilation into hadrons to that for muon pairs. A great deal of data has been accumulated on the  $\psi$  and  $\psi'$  in the interim and many of their properties and decay modes have been established. Perhaps more importantly, the past few months have seen rather restrictive limits put on possible decays which were expected to be present in many theories of the new resonances.

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As we shall see, there is considerable evidence that the  $\psi$ 's are hadrons. The major open questions revolve around exactly what is the new quantum number(s) associated directly or indirectly with the new particles. Most importantly, if there is at least one new additive quantum number and associated new quark(s), with the  $\psi$ 's being bound states of a new quark and antiquark, the continued absence of evidence either for other expected new quark-new antiquark states or for particles containing only one new quark (and therefore the new quantum number) is becoming more and more of a puzzle. But before treating these questions, let us set the stage for the whole discussion by considering briefly the behavior of the total cross section for electron-positron annihilation into hadrons.

## ELECTRON-POSITRON ANNIHILATION INTO HADRONS

The total cross section for electron-positron annihilation through one photon into hadrons has a simple theoretical interpretation when divided by the (theoretical) cross section for electron-positron annihilation through one photon into muon pairs. If the annihilation into hadrons is viewed as occurring via the creation of fermion-antifermion pairs, followed by their rearrangement into the more familiar hadrons which one actually finds in the final state, then

$$R = \frac{\sigma_{\rm T}(e^+e^- \rightarrow \rm hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$
(1)

is the sum of the squares of the charges of the operative fundamental fermions making up the hadrons found in the final state. With three fractionally charged Gell-Mann-Zweig quarks,  $^{4, 5}$  one expects

$$R = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3} \quad , \tag{2}$$

while if each quark comes in three colors,

$$R = 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) = 2 \qquad (3)$$

The published data<sup>3, 6, 7</sup> on R are summarized in Fig. 1. After the  $\rho$ ,  $\omega$ , and  $\phi$  resonances, R seems to settle on a value between 2 and 3 for center-of-mass energies,  $\sqrt{Q^2} \leq 3.6$  GeV. Following the rapid rise in the 4-GeV region (and possible broad resonance at  $\approx 4.1$  GeV), Fig. 1 and more recent results<sup>8</sup>, <sup>9</sup>, <sup>10</sup> show that R lies between 5 and 6 up to a value of  $\sqrt{Q^2}$  of 7.4 GeV.

The measured value of R below  $\sqrt{Q^2} \sim 3.6$  GeV is very suggestive of the theoretical prediction of 2 for colored quarks. Thus, below the  $\psi$ 's, electron-positron annihilation, as well as many other parts of particle physics, is quite consistent with the three colored quark model predictions. It is also quite suggestive from Fig. 1 to associate the  $\rho$ ,  $\omega$ , and  $\phi$ , which are quark-antiquark bound states of the three Gell-Mann-Zweig quarks, with the R value of 2 to 3 until  $\sqrt{Q^2}$  nears 4 GeV. Very similarly, the  $\psi(3100)$ ,



Fig. 1.  $R = \sigma_T (e^+e^- \rightarrow hadrons) / \sigma (e^+e^- \rightarrow \mu^+\mu^-)$  from measurements at Orsay, <sup>6</sup> Frascati, <sup>7</sup> and SLAC.<sup>3</sup>

 $\psi'(3700)$ , and possible  $\psi''(4100)$  would be associated with the jump in R to a value of 5 to 6. If the step in R is taken as the physical threshold for the production of hadrons containing new quarks, with a corresponding change in the sum of the squares of the quark charges, the  $\psi$ 's are then to be regarded as the corresponding bound states of new quarks and new antiquarks. As such, the  $\psi$ 's are hadrons containing a "hidden quantum number" character-izing the new quarks. While this picture is at least suggestive, we shall see shortly independent evidence that the  $\psi$ 's are hadrons.

## THE $\psi(3100)$

As shown in Fig. 2, the cross sections for electron-positron annihilation into hadrons,  $\mu^+\mu^-$ , and  $e^+e^-$  all have large enhancements just below 3100 MeV. With the new calibration of the SPEAR storage ring, the mass of the resonance<sup>11</sup> is  $3095 \pm 4$  MeV. Various properties of the resonance now can be determined from examination of the data<sup>11</sup> in Fig.<sup>5</sup>2.

# $_{\rm J}{}^{\rm PC}$

There is an interference of about three standard deviation significance between the resonant-amplitude and the quantum electrodynamic amplitude in  $e^+e^- \rightarrow \mu^+\mu^-$ . As seen in Fig. 3a, it is destructive below the resonant energy.

The observation of an interference and the symmetry of the detector with respect to space and charge demands P = C = -1 for the resonance. There is no evidence for a charge asymmetry in  $e^+e^- \rightarrow \mu^+\mu^-$  (Fig. 3b), so the data are consistent with there being a single eigenstate of C and P.



Fig. 2. The cross section for (a)  $e^+e^- \rightarrow hadrons$ , (b)  $e^+e^- \rightarrow \mu^+\mu^-$ , and (c)  $e^+e^- \rightarrow \mu^+\mu^-$  vs. centerof-mass energy. The latter two cross sections are integrated over the range  $|\cos \theta| \leq 0.6.11$ 

Fig. 3. (a) The ratio of  $\mu^+\mu^-$  to e<sup>+</sup>e<sup>-</sup> yield vs. center-of-mass energy. (b) The front-back asymmetry of  $\mu$  pairs vs. center-ofmass energy.<sup>11</sup>



Fig. 4. (a) The angular distribution in  $e^+e^- \rightarrow e^+e^-$  at the  $\psi$ . Also shown is the result of subtracting QED.<sup>11</sup> (b) The angular distribution in  $e^+e^- \rightarrow \mu^+\mu^-$  at the  $\psi$ . The solid curves are  $1 + \cos^2 \theta$ .

Furthermore, as the quantum electrodynamic amplitude for  $e^+e^- \rightarrow \mu^+\mu^-$  has only helicity ±1 parts, for an interference to exist  $J \neq 0$ . The sign of the interference and/or the form of the angular distribution on resonance then excludes<sup>11</sup> everything except J=1. As seen in Fig. 4, the  $1 + \cos^2 \theta$  angular distribution expected for J=1 is consistent with the data for both  $e^+e^- \rightarrow \mu^+\mu^$ and  $e^+e^- \rightarrow e^+e^-$  (after subtraction of the quantum electrodynamic cross section).

## Widths

1

With the establishment of J=1, the width for  $\psi$  decay into some particular channel, i, can be obtained by integrating the cross section for production of that channel over the resonance,

$$\int_{\text{Res}} \sigma(e^+e^- \to i) \, d \sqrt{Q^2} = \frac{6\pi^2}{M^2} \frac{\Gamma_{ee}\Gamma_i}{\Gamma_{total}} \, . \tag{4}$$

Assuming that  $\Gamma_{\text{total}} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\text{hadrons}}$ , the data in Fig. 2 will on integration give us separately  $\Gamma_{ee}$ ,  $\Gamma_{\mu\mu}$ ,  $\Gamma_{\text{hadrons}}$  and  $\Gamma_{\text{total}}$ . Where they are comparable, the data from DESY, <sup>12</sup> Frascati<sup>13</sup> and SLAC<sup>11</sup> are in agreement on the resulting widths.

The widths for these channels, as well as widths (or upper limits) for decay into various specific final states are given in Table I.

Mode	Width	Reference
e <sup>+</sup> e <sup>-</sup>	$4.8 \pm 0.6 \text{ keV}$	11
μ+μ-	$4.8 \pm 0.6 \text{ keV}$ 69 ± 15 keV	11
hadrons	59 ± 14 keV	11
$\gamma\gamma$	$\leq 0.035 \Gamma_{\mu\mu} = .17 \text{ keV}$	14
π <sup>+</sup> π <sup>-</sup>	$< 0.0046 \Gamma_{,,,,} = .022 \text{ keV}$	15
<b>κ</b> <sup>+</sup> <b>κ</b> <sup>-</sup>	< $0.0084 \Gamma_{\mu\mu} = .040 \text{ keV}$	15
K <sub>S</sub> K <sub>L</sub>	$< 0.0002 \Gamma_{\rm hadrons} = .012  \rm keV$	9, 10
π <sup>o</sup> γ	$< 0.005 \Gamma_{\rm hadrons} = 0.3  \rm keV$	16
ηγ	$0.1 \text{ keV} < \Gamma < 2 \text{ keV}$	14
$4\pi^{\pm}$	(.004 ± .001) $\Gamma_{\rm total}$	9,10,17
$6\pi^{\pm}$	$(.004 \pm .002) \Gamma_{\text{total}}$	9, 10, 17
πρ	$(.013 \pm .003) \Gamma_{\rm total}$	9, 10, 17
$4\pi^{\pm}\pi^{0}$ including $\omega\pi^{+}\pi^{-}$ and $\rho\pi\pi\pi$	$(.04 \pm .01) \Gamma_{\text{total}}$	9,10,17
$6\pi^{\pm}\pi^{\circ}$ including $\omega\pi\pi\pi\pi$	$(.029 \pm .007) \Gamma_{\rm total}$	9, 10, 17
$8\pi^{\pm}\pi^{0}$	$(.009 \pm .003) \Gamma_{total}$	9,10,17
KŘπ		
к <sup>о</sup> К <sup>о*</sup> (890) + К <sup>о</sup> К <sup>о*</sup> (890)	$(.0024 \pm .0005) \Gamma_{table}$	9.10
K <sup>+</sup> R <sup>-*</sup> (890) + R <sup>-</sup> K <sup>+*</sup> (890)	$(.0031 \pm .0007) \Gamma_{,1}$	9,10
$K^{0}\overline{K}^{0**}(1420) + \overline{K}^{0}K^{0**}(1420)$	<.0019 $\Gamma_{total}$	9,10
$K^{+}\overline{K}^{-**}(1420) + K^{-}K^{+**}(1420)$	$<.0019 \Gamma_{total}$	9,10
$K \overline{K} \pi \pi$	iotat	
$K^{0*}(890)\overline{K}^{0**}(1420) + \overline{K}^{0*}(890)K^{0**}(1420)$	$(.0037 \pm .0010) \Gamma_{total}$	9, 10
$K^{0^*}(890)\overline{K}^{0^*}(890) + \overline{K}^{0^*}(890)K^{0^*}(890)$	$<.0006 \Gamma_{total}$	9,10
$K^{0**}(1420)\overline{K}^{0**}(1420) + \overline{K}^{0**}(1420)K^{0**}(1420)$	< . 0018 <sup>Γ</sup> total	9, 10
$KR_{\pi\pi\pi}$	seen	17
$K^{+}K^{-}4\pi^{\pm}$	$(.003 \pm .001) \Gamma_{total}$	9, 10
ηφ	seen	17
_	$(.036 \pm .01) \Gamma_{iii} = .17 \pm .05 \text{ keV}$	15
pp	$(.0021 \pm .004) \Gamma_{\text{total}} = .15 \pm .03 \text{ keV}$	9,10
ΔĀ	$(.0016 \pm .0008) \Gamma_{total}$	9,10
$N\overline{N}\pi$	(.0037 ± .0019) $\Gamma_{\text{total}}$ for $p\bar{p}\pi^{0}$ , $p\bar{n}\pi^{-}$ , and $n\bar{p}\pi^{+}$	9,10
$p\bar{p}\pi^+\pi^-$	seen	17

Table I Decay modes and widths for the  $\psi$ (3100)

One Photon Intermediate State Phenomenology

Just as for any other vector meson, one may define a photon-vector meson coupling. If  $eM_{\eta_{l}}^{2}/f_{\eta_{l}}$  enters the amplitude at the  $\gamma$ - $\psi$  vertex, then

$$\Gamma_{ee} = \frac{4\pi\alpha^2}{3} \left( \frac{M_{\psi}}{f_{\psi}^2} \right)$$
(5)

The leptonic width in Table I translates into

$$f_{\psi}^2/4\pi \simeq 11 \quad , \qquad (6)$$

a value comparable to that<sup>6</sup> for the  $\rho (\approx 2.5)$ ,  $\omega (\approx 19)$ , and  $\phi (\approx 11)$ .

Moreover, the existence of  $\psi \to \gamma \to e^+e^-$  implies the existence of  $\psi \to \gamma \to$  hadrons with a width .

$$\Gamma(\psi \rightarrow \gamma \rightarrow \text{hadrons}) = R \Gamma_{ee}$$
  
=  $12 \pm 2 \text{ keV}$  . (7)

In particular, the decays  $\psi \to 4\pi^{\pm}$  and  $\psi \to 6\pi^{\pm}$  are compatible with proceeding via the one photon intermediate state, since the ratios  $4\pi^{\pm}/\mu^{+}\mu^{-}$  and  $6\pi^{\pm}/\mu^{+}\mu^{-}$  are the same on and off the resonance within errors. If  $\psi \to \pi^{+}\pi^{-}$  also occurs via one photon, the upper bound<sup>15</sup> on the width in Table I gives a bound on the pion form factor at the  $\psi$  mass:

$$|F_{\pi}((3.1 \text{ GeV})^2)|^2 < 0.02$$
 (8)

This bound is now sufficiently tight that it is comparable to what would be expected using a monopole form factor to extrapolate  $F_{\pi}(Q^2)$  from the  $Q^2 \simeq 1$  GeV<sup>2</sup> region.

## Direct Decay Phenomenology

Since  $\Gamma_{\text{hadrons}}$  is much larger than Eq. (7), there must exist other hadronic decays. In particular, the decays of the  $\psi$  into  $3\pi$ ,  $5\pi$ , and  $7\pi$  occur at rates much too large to be compatible with proceeding through a single photon intermediate state. 9, 10, 17 By definition, these are then "direct decays." They are characterized by G=-1. Since C=-1, we have I=0 or 2. The choice of I=0 then follows from the existence of direct decays like  $\Lambda\bar{\Lambda}$ ,  $p\bar{p}$ , KK\*(890) or from the ratio of  $\pi^+\rho^-$ : $\pi^-\rho^+$ : $\pi^0\rho^0$  in the  $3\pi$  decays.9, 10, 17

With the assignment G = -1 and I = 0 for direct decays, it is possible to calculate or estimate some of the final states which involve multineutrals using measured widths. For example, one can show that 18, 19

$$\left(\frac{3}{2}\right)\Gamma(4\pi^{\pm}\pi^{0}) = \Gamma(5\pi)$$
(9a)

$$\frac{3}{2}\Gamma(6\pi^{\pm}\pi^{O}) \leq \Gamma(7\pi) \leq 3\Gamma(6\pi^{\pm}\pi^{O})$$
(9b)

$$\Gamma(N\overline{N}\pi) = 6\Gamma(p\overline{p}\pi^{0})$$
(9c)

$$\Gamma(K\overline{K}\pi) = 3\Gamma(\overline{K}_0K^+\pi^-)$$

$$= 3\Gamma(K_SK^+\pi^- + K_SK^-\pi^+)$$
(9d)

$$3\Gamma(\mathbf{K}^{\dagger}\mathbf{K}^{-}\pi^{+}\pi^{-}) \leq \Gamma(\mathbf{K}\overline{\mathbf{K}}\pi\pi) \leq 6\Gamma(\mathbf{K}^{\dagger}\mathbf{K}^{-}\pi^{+}\pi^{-})$$
(9e)

Out of all hadronic decays involving the  $\psi(3100)$ , 20% occur through the one photon intermediate state. Of the direct decays, we may use the observed widths in Table I together with Eqs. (9) and statistical models of the charge distribution in high multiplicity states to estimate that 20% to 30% of the hadronic modes consist of odd numbers of pions. The inclusive kaon spectrum together with the observed decays into particular channels indicates that another 20% to 30% of the hadronic decays involve  $K\bar{K}+n\pi$ 's. With another 5% to 10% of the decays of the form  $N\bar{N}+n\pi$ 's, we have accounted for 65% to 90% of the hadronic  $\psi(3100)$  decays. We still have the possibility of decays involving  $\eta$ 's and those with a photon + hadrons, both of which are certainly there, at some level, inasmuch as  $\eta\phi$  and  $\eta\gamma$  are seen. There is not a clear gap between the total hadronic width and the combined width for decays of the  $\psi(3100)$  which one can reconstruct completely or can reasonably estimate on the basis of what is seen.

## SU(3)

If the  $\psi$  acts in its direct decays like it has I=0, it could be an SU(3) singlet or the eighth component of an octet.<sup>20</sup>By studying its decay modes, it is possible to decide if it acts like a singlet or octet or some mixture of the two like the  $\omega$  and  $\phi$ .

First consider the decay  $\psi \rightarrow M_1 + M_2$ , where  $M_1$  and  $M_2$  are mesons belonging to octets with the same  $\mathscr{C}$ , the SU(3) generalization of charge conjugation.  $\mathscr{C}$  is the same as ordinary charge conjugation, C, for a singlet and is defined for an octet as equal to C of its third or eighth component. An example of a decay into two octets with the same  $\mathscr{C}$  is  $\psi \rightarrow$  pseudoscalar + pseudoscalar, the relative widths for which are collected in Table II assuming SU(3) invariance and the two possible assignments<sup>21</sup> for the  $\psi$  in its direct decays or its decay through a photon.

We note that for an SU(3) singlet <u>all</u> decays into two pseudoscalars are forbidden, but that for the eighth component of an octet (or any mixture of an octet and singlet)  $\psi \not\rightarrow \pi^+\pi^-$  but  $\psi \rightarrow K^+K^-$  and  $K_SK_L$  at equal rates. Since, as shown in the table, the second order electromagnetic decay into  $K_SK_L$  is forbidden by SU(3), the observation of  $\psi \rightarrow K_SK_L$ , or lack of it, reflects most sharply on the SU(3) assignment of the  $\psi$  in its direct decays.

With appropriate substitutions, Table II is applicable to decays into pseudoscalar + tensor, vector + vector, tensor + tensor, etc. Thus the

Table II Relative rates<sup>22</sup> for  $\psi$  decays into two pseudoscalar mesons assuming SU(3) invariance and the final state being an SU(3) singlet, an eighth component of an octet, or a combination of the third and eighth components of an octet characteristic of the photon.

Mode	£	SU(3) Assignmen	t
	$\overset{1}{\backsim}$	*	ייץיי
$\pi^+\pi^-$	0	0	1
$\pi^{\circ}\pi^{\circ}$	0	0	0
к*к-	0	1	1
K <sub>S</sub> K <sub>L</sub>	0	1	0
ηη	0	0	0

upper limits in Table I on decays into  $K_SK_L$ ,  $KK^{**}(1420)$ ,  $K^{*}(890)$ ,  $K^{*}(890)$ , and  $K^{**}(1420)$   $K^{**}(1420)$  all point to the  $\psi(3100)$  being an SU(3) singlet. The absence of any particular decay may always be attributable to a quirk of the dynamics. But the systematic lack of observation of decay modes prohibited for an SU(3) singlet, while at the same or higher decay rate level several modes allowed for a singlet are seen, is a fairly strong indication both that SU(3) is operative and that the  $\psi(3100)$  is a singlet.

Second, consider the decay of the  $\psi$  into two meson octets which have opposite values of  $\mathscr{C}$ . Table III gives the relative intensities for the decay into a pseudoscalar meson + vector meson, which is a particular example of such a decay, under the assumption of different SU(3) assignments for the  $\psi$ or for decay through a photon. This table also can be easily transcribed to decays into a vector meson + tensor meson, vector meson + scalar meson, etc.

Since  $\overline{K}^{0}K^{*0}/\overline{K}^{-}K^{**}$  is not ~4 (and  $\eta_{\rho}/\pi^{0}\rho^{0}$  is not ~3) from the data in Table I, the observed decays of the  $\psi(3100)$  into a pseudoscalar meson + vector meson cannot be occurring through a one photon intermediate state. Taking them as direct decays, however, and comparing the preliminary decay width for  $K^{0}\overline{K}^{*}(890)^{0}$  or  $K^{+}\overline{K}^{*}(890)^{-}$  (which are compatible with being equal) with that for  $\pi^{0}\rho^{0}$  from Table I gives results more compatible with the  $\psi$  being the eighth component of an octet than a singlet. <sup>23</sup> One should be aware that the comparison of the  $\pi_{\rho}$  and KK\* decay rates involves rather different detection efficiences and corresponding corrections in going from the raw data to the numbers in Table I. If the  $\psi$  is a singlet, it is difficult to see why SU(3) should be broken so strongly (by 50% or more in the amplitude). This is especially so when the  $\psi$  doesn't have any observed direct

Table III Relative rates<sup>22</sup> for  $\psi$  decays into a pseudoscalar meson + vector meson assuming SU(3) invariance and the final state being an SU(3) singlet, an eighth component of an octet, or a combination of the third and eighth components of an octet characteristic of a photon.  $V^8 \simeq \sqrt{1/3} \ \omega + \sqrt{2/3} \ \phi$  and  $\eta^8$  are the eighth members of the vector and pseudoscalar octets, respectively.

Mode	1	SU(3) Assignm	nent
	1	8	''γ''
$\pi^+\rho^- = \pi^-\rho^+ = \pi^0\rho^0$	1	1	1
$K^{+}\overline{K}^{*-} = \overline{K}^{-}K^{*+}$	1	1/4	1
$K^{O}\overline{K}^{*O} = \overline{K}^{O}K^{*O}$	1	1/4	4
$\eta^8 v^8$	1	1	1
$\eta^8 \rho$	0	0	3
$\pi^{0}v^{8}$	0	0	3

decays into two mesons with the same value of  $\mathscr{C}$ , which are forbidden for a singlet, but does have sizable pseudoscalar + vector and vector + tensor decays, which are allowed for a singlet.

For decays into baryon-antibaryon, clear tests of the SU(3) character of the  $\psi$  are more difficult to find since an SU(3) octet has two possible couplings to  $B\overline{B}$ , as indicated in Table IV.

The absence of  $\Lambda \overline{\Sigma^{0}} + \overline{\Lambda} \Sigma^{0}$  at six times the rate of  $\Lambda \overline{\Lambda}$  can be used to eliminate the possibility of an important contribution from an intermediate photon. The relative rates for  $p\overline{p}$  versus  $\Lambda \overline{\Lambda}$  given in Table I are consistent with those expected for an SU(3) singlet, especially if corrected for phase space, <sup>24</sup> but a particular choice of F/D can accomplish the same result. Some observations on SU(3) and the decay of the  $\psi$  into  $\pi^{0}\gamma$  and  $\eta\gamma$  will be deferred until we discuss  $\psi'(3700) \rightarrow \eta \psi(3100)$ .

The SU(3) character of  $\psi$  decays is of some importance, both for specific theoretical schemes, such as charm<sup>25</sup> where the  $\psi$  is an SU(3) singlet<sup>26</sup> and more generally for understanding the electromagnetic current which until last year was consistent with only containing SU(3) octet pieces. For if SU(3) is conserved in the  $\gamma$ - $\psi$  coupling and in  $\psi$  - hadrons, then an SU(3) singlet character of the final hadron state implies an SU(3) singlet part of the electromagnetic current. Note that the weak link in this chain of argument may be  $\psi$  - hadrons, for the narrow width for direct decays indicates that something in this coupling is not typical of most strong interactions. It is

Table IV Relative rates for  $\psi$  decays into baryon + antibaryon assuming SU(3) invariance and the final state being an SU(3) singlet, an eighth component of an octet (with antisymmetric and symmetric couplings F and D, respectively), or a combination of the third and eighth components of an octet characteristic of a photon (with antisymmetric and symmetric couplings F' and D', respectively).

Mode	SU(3) Assignment		
	1	~	ייץיי
$\Lambda ar{\Lambda}$	1	1	1
$\Sigma^{O}\overline{\Sigma}^{O}$	1	1	1
$\Sigma^{+}\overline{\Sigma^{+}}$	1	- 1	$(1+3 {\rm ~F'/D'})^2$
$\Sigma^{-}\overline{\Sigma^{-}}$	1	1	$(1 - 3 F'/D')^2$
pp	1	$\left(\frac{1}{2} - \frac{3F}{2D}\right)^2$	(1+3 F'/D') <sup>2</sup>
nn	1	$\left(\frac{1}{2} - \frac{3F}{2D}\right)^2$	4
	1	$\left(\frac{1}{2} + \frac{3F}{2D}\right)^2$	4
	1	$\left(\frac{1}{2} + \frac{3F}{2D}\right)^2$	(1 - 3 F'/D') <sup>2</sup>
$\Lambda \Sigma^{\mathbf{O}}$	0	0	3
λΣ <sup>ο</sup>	0	0	- 3

even possible that the decay mechanism acts as a "filter" between the SU(3) properties of the  $\psi$  and the final state, allowing mostly the singlet component to be carried to the hadrons. But if the electromagnetic current does have a singlet component, then independent of particular theoretical schemes such as charm or color, we will have added a new piece to the electromagnetic current of hadrons for the first time in twenty years.

# Conclusions on the $\psi(3100)$

The  $\psi(3100)$  has  $J^{PC} = 1^{--}$  and has both decays through one photon and direct decays into hadrons. There is strong evidence that it acts as a G = -,

I=0 object in its direct decays. There is also evidence, although somewhat contradictory, pointing to the direct decays being those of an SU(3) singlet. More than any evidence from photoproduction or its observation in hadronic collisions, this observance of strong interaction symmetries in the direct decays indicates the  $\psi(3100)$  is a hadron. Its small width is at least qualitatively understood theoretically if it is a new quark-new antiquark bound state, since then the empirical rule<sup>27</sup> forbidding quarks and antiquarks in the same particle from annihilating each other in decay amplitudes would strongly suppress the probability that the new quark and new antiquark in the  $\psi$  annihilate and form hadrons composed of "old" quarks.<sup>28</sup>

### THE $\psi'(3700)$

With the discovery of the first new particle, a careful scan for other such states was soon begun. This resulted quickly in the discovery<sup>2</sup> of a second such state with a mass of  $3684 \pm 5$  MeV.

# $J^{PC}$ and Widths

The properties of this state can be established in much the same way as for the  $\psi(3100)$ . Recently analyzed data<sup>9</sup>, <sup>10</sup> from the SLAC-LBL magnetic detector establishes that  $J^{PC} = 1^{--}$  for the  $\psi'(3700)$  through observation of an interference of the resonant and quantum electrodynamic amplitudes in  $e^+e^- \rightarrow \mu^+\mu^-$ . The decay widths of the  $\psi'$  are then obtained from Eq. (4): present information is summarized in Table V. Extraction of a  $\gamma - \psi'$  coupling from the leptonic width results in  $f_{\psi}^2/4\pi \simeq 30$ .

#### $\psi^{\dagger} \rightarrow \pi \pi \psi$

The  $observation^{29}$  of this mode is shown in Fig. 5. The two pions are dominantly in an s-wave, isospin zero state, so that if this is an isospin conserving decay, the  $\psi$ ' has I=0 (and G=-) like the  $\psi$ . The mass spectrum of the two pions is strongly peaked (after phase space and detection efficiency are taken out) toward the high end. 31, 32Several recent theoretical papers papers<sup>33, 34, 35</sup> have attempted to explain this peaking by invoking an Adler zero in the amplitude. While qualitatively in the right direction, it is not yet clear that this explanation, with a linear zero in the amplitude, can be made to agree quantitatively with both the observed  $\psi' \rightarrow \pi \pi \psi$  and  $\pi \pi \rightarrow \pi \pi$  amplitudes without moving the zero above  $\pi\pi$  threshold.





Mode	Width	Reference
$e^+e^- = \mu^+\mu^-$	$2.2 \pm 0.3 \text{ keV}$ 225 ± 56 keV	9,10
hadrons	$220 \pm 56 \text{ keV}$	
$\psi$ + anything	$(.57 \pm .08) \Gamma_{hadrons}$	29
$\psi \pi^+ \pi^-$	(.32 ± .04) $\Gamma_{hadrons}$	29
ψη	(.04 $\pm$ .02) $\Gamma_{hadrons}$	9,10
$X\gamma \rightarrow \psi\gamma\gamma$	$\leq .066 \Gamma_{hadrons}$	9,10
$\gamma + X$	$\leq$ (.01 to .07) $\Gamma_{hadrons}$	30,31
	for X narrow	
$\pi^{O}\rho^{O}$	$\leq$ (.001) $\Gamma_{\rm hadrons}$	9,10,17
$4\pi^{\pm}\pi^{O}$	$\leq$ (.007) $\Gamma_{\rm hadrons}$	9,10
qq	$\leq$ (.0003) $\Gamma_{\text{hadrons}}$	9,10

Table V Decay modes and widths for the  $\psi'(3700)$ .

 $\psi' \rightarrow \eta \psi$ 

This confirms that the  $\psi$  and  $\psi'$  have the same isospin and G parity. If the  $\eta$  were purely in an octet and the  $\psi$  and  $\psi$  were singlets, <sup>36</sup> the decay  $\psi' \rightarrow \eta \psi$  would be forbidden in the limit of SU(3) invariance. With this in mind, the rate given in Table V is rather large, since compared to the swave decay  $\psi' \rightarrow \pi \pi \psi$  (which has no reason to be suppressed by SU(3)) the pwave  $\psi' \rightarrow \eta \psi$  mode has little phase space available. Conversely, if the observed  $\psi' \psi \eta$  coupling is coming purely from the small<sup>37</sup> singlet piece of the physical  $\eta$ , then the  $\psi' \psi \eta'$  coupling must be quite strong.

The strength of the  $\psi'\psi\eta$  coupling may be related to another possible difficulty with the singlet assignment of the  $\psi$ 's. If the  $\eta$  were purely in an octet and the  $\psi$  a singlet,

$$\frac{\Gamma(\psi \to \pi^{0} \gamma)}{\Gamma(\psi \to \eta^{8} \gamma)} = 3 \quad . \tag{10}$$

This is on the edge of being in disagreement with experiment (see Table I). However, a naive application of  $\psi^{\dagger}$  vector dominance to the amplitude for  $\psi \rightarrow \eta \gamma$ , together with the  $\gamma - \psi^{\dagger}$  and  $\psi^{\dagger} \psi \eta$  couplings extracted from Table V, yields a value<sup>38</sup> for  $\Gamma(\psi \rightarrow \eta \gamma)$  which is in the range indicated by experiment in Table I. Thus, whether due to SU(3) breaking, the singlet component of the physical  $\eta$ , or an incorrect SU(3) assignment of the  $\psi$  or  $\psi'$ , the apparent experimental discrepancy with Eq. (10) and the relatively large  $\psi'\psi\eta$  coupling are likely coupled theoretical problems.<sup>39</sup>

# $\psi' \to \gamma X \to \gamma \gamma \psi$

Within the charmonium explanation<sup>26</sup> of the new resonances as s-wave charmed quark-charmed antiquark bound states, one expects<sup>40, 41</sup> p-wave bound states to lie between the  $\psi$  and  $\psi'$ . In addition, within any model that proposes new quarks to explain the rise in R and the new particles, one expects  ${}^{1}S_{0}$  pseudoscalar states to be nearby in mass to the  ${}^{3}S_{1}$  vector ( $\psi$  and  $\psi'$ ) states. The  ${}^{1}S_{0}$  and  ${}^{3}P_{J}$  states (with J=0, 1, 2) have the appropriate quantum numbers to allow the decay  $\psi' \rightarrow \gamma X$ , followed by  $X \rightarrow \gamma \psi$ . Early charmonium calculations<sup>26, 40, 42</sup> predict a combined width of several hundred keV for  $\psi' \rightarrow \gamma + {}^{3}P_{J}$  via electric dipole transitions, and then  ${}^{3}P_{J} \rightarrow \gamma \psi$ being the overwhelmingly dominant decay of these p-wave states.

The sum of all such gamma ray cascade decays passing through either  ${}^{3}\mathrm{P}_{J}$  or  ${}^{1}\mathrm{S}_{0}$  states may be bounded by looking at the mass squared distribution of the neutrals in  $\psi' \rightarrow \psi$  + neutrals.  ${}^{43}$  This follows since parity conservation demands that for a decay of the form  $\psi' \rightarrow \gamma X \rightarrow \gamma \gamma \psi$ ,  $M_{\gamma\gamma}^{2}$  be symmetrical about the midpoint of its distribution. But the neutral mass spectrum in  $\psi' \rightarrow \psi$  + neutrals is strongly peaked toward high masses.  ${}^{32}$  Thus the depletion of events below  $1/2(\mathrm{M}_{\psi'}-\mathrm{M}_{\psi})^{2}$  gives a tight bound on the sum of all decays of the form  $\psi' \rightarrow \gamma X \rightarrow \gamma \gamma \psi$ . The limit in Table V obtained using this method is more than an order of magnitude below the naive theoretical expectations. Alternately, after  $\eta\psi$  and  $\pi^{0}\pi^{0}\psi$  events are subtracted from the neutrals spectrum, this provides a method of searching for such cascade decays with small branching ratios.

## $\psi' \rightarrow hadrons$

Motivated by the potential model calculations of quark-antiquark bound states, particularly those of the charmonium type,  $^{26}$ ,  $^{40}$ ,  $^{41}$  one might guess that the rates for  $\psi$  or  $\psi$ ' decay into leptons and into hadrons are both proportional to the bound state wave function squared at the origin. In that case, one expects for direct decays<sup>44</sup>

$$\Gamma(\psi' \to \text{hadrons}) \simeq \Gamma(\psi \to \text{hadrons}) \frac{\Gamma(\psi' \to \text{ee})}{\Gamma(\psi \to \text{ee})}$$
$$\simeq 22 \text{ keV} , \qquad (11)$$

i.e., direct decays of the  $\psi'$  are ~10% of all the hadronic decays. The upper limits on  $\pi^{0}\rho^{0}$ ,  $4\pi^{\pm}\pi^{0}$  and  $p\bar{p}$  in Table V are all consistent with Eq. (11) and indicate that the absolute value of the  $\psi'$  width into these channels is less than that for the  $\psi$  into the same channels. In other words, if the direct decays of the  $\psi'$  have the same pattern as those of the  $\psi$ , the experimental results in Table V indicate a width for  $\psi'$  direct decays to hadrons less than

$$\Gamma(\psi \rightarrow \text{hadrons})_{\text{direct}} \simeq 47 \text{ keV}$$

Decays of the  $\psi$ ' through one photon into hadrons are calculated to be

$$\Gamma(\psi' \to \gamma \to \text{hadrons}) = R \Gamma(\psi' \to e^+ e^-)$$

$$\simeq 6.6 \text{ keV} \quad . \tag{12}$$

This is  $\approx 3\%$  of the total width.

## Missing Decays of the $\psi^{\dagger}$

Totalling up the decays of the  $\psi'$  which are observed or can be reasonably estimated, we have from  $\psi' \rightarrow \psi$  + anything,  $\psi' \rightarrow$  hadrons (direct decays), and  $\psi' \rightarrow \gamma \rightarrow$  hadrons a sum of ~70% of  $\Gamma_{\text{total}}$ . What are the roughly 30% of  $\psi'$  decays which contain multihadrons and trigger the detectors but have not been completely reconstructed ör reasonably accounted for? Can there be other narrow states, X, into which the  $\psi'$  decays, such that there are two or more neutrals in the resulting final state?

If X has C=+ and either I=0 or 1,  $\psi' \rightarrow \gamma X$  and one faces the bounds on the gamma ray decays of the  $\psi'$ , independent of whether the state X decays into at least one neutral in most of its decays. If X has C=- and I=0, then one has  $\psi' \rightarrow \pi^0 \pi^0 X^0$  but also  $\psi' \rightarrow \pi^+ \pi^- X^0$ , so that the state X should show up as a peak (like the  $\psi$ ) in Fig. 5 recoiling against two charged pions in a relative s-wave I=0 state.<sup>45</sup> If X has C=- and I=1, then  $\psi' \rightarrow \pi^0 X^0$ , but also  $\psi' \rightarrow \pi^{\pm} X^{\mp}$ , and there should be a monochromatic pion line.

Another possibility is  $\psi' \to X\overline{X}$  with X decaying into at least one neutral much of the time. The difficulty here is that with a strong coupling of the  $\psi'$  to  $X\overline{X}$ ,  $2M_X$  would have to be just a few MeV away from  $M_{\psi'}$  to keep the width for  $\psi' \to X\overline{X}$  below ~100 keV. But then the X particles are created almost at rest and one may make constrained fits to all charged particles or all charged particles plus one neutral using  $M_{\psi'}/2$  as the energy, and zero as the momentum of the X. Needless to say, there is no evidence from these fits for such an X particle.

This leaves us with basically three outs if our estimate for direct decays of the  $\psi$ ' is correct: (a) Some of the experiments are wrong; (b) the X states are much wider than we expect, invalidating the experimental limits; or (c) there are many such states, X, and each one contributes a few percent of the total width of the  $\psi$ . Theoretically, at least possibility (b) is not particularly appetizing.

### PRODUCTION OF THE NEW PARTICLES

We have already discussed in some detail  $\psi$  and  $\psi'$  production in electronpositron colliding beams. If the structure<sup>3</sup> at ~4.1 GeV (see Fig. 1) is a resonance, its total width is 250 to 300 MeV and its leptonic width,  $\Gamma_{ee} \simeq 4$ keV. A search for other narrow resonances now extends up to masses of 7.6 GeV with no additional narrow states found. <sup>46,9</sup>, 10

In hadronic reactions, the  $\psi$  has been observed in pN, nN, and  $\pi N$  collisions at BNL, <sup>1</sup> FNAL, <sup>47</sup>, <sup>48</sup> and CERN. <sup>49</sup> The theoretical treatment of

these matters already forms a large subject in itself, which there is no space for here.

The  $\psi$  has also been photoproduced at FNAL, <sup>50</sup> SLAC, <sup>51, 52</sup> and Cornell. <sup>53</sup> The  $\psi$ ' is also observed at SLAC<sup>52</sup> and FNAL. <sup>54</sup> Figure 6 shows some of the recent results from the SLAC-Wisconsin experiment. <sup>52</sup> Since the value of  $d\sigma/dt(\gamma N \rightarrow \psi N)$  at t=0 extracted from the FNAL experiment<sup>50</sup> at E<sub> $\gamma$ </sub> ~ 100 GeV is only a factor of two or so above the 21-GeV data,

it is clear that most of the rise from threshold in the cross section for  $\psi$ photoproduction occurs by ~20 GeV. A straightforward application of the vector dominance model assuming purely imaginary amplitudes leads to values of the  $\psi$ N and  $\psi$ 'N total cross sections of ~1 mb. Using the measured slope in  $\gamma N \rightarrow \psi N$  for  $\psi N \rightarrow \psi N$  leads to an elastic  $\psi N$ cross section which is only a few percent of the total cross section.

## CONCLUSIONS

The evidence from the decay modes of both the  $\psi$  and  $\psi$ ' strongly indicates they are both hadrons with I=0 and G=-1. The large width of the  $\psi''(4100)$ , if it is a resonance, is certainly that characteristic of a hadron. Especially when coupled with the observation of the step in R near 4 GeV, this points to the existence of some new hadronic degree(s) of freedom. This is most simply to be associated with new quarks carrying a new additive or multiplicative quantum number. The  $\psi$ 's would be bound states of a new quark and new antiquark.

However, all the popular choices for the new quantum number(s) and associated quark(s) are in some difficulty. If the  $\psi$ 's are colored states, <sup>55</sup> one immediately faces at least the question of why the  $\psi$  and  $\psi$ ' are not much wider with most decays involving a photon.

In the charm scheme,  $^{25}$ ,  $^{26}$ where one new quark is added with charge + 2/3, the lack of evidence





for substantial radiative decays of the  $\psi'$  into the p-wave states and the lack of approach of R to the charm prediction of 3 1/3 are particularly bothersome. Moreover in any model<sup>56,57</sup> with an additive quantum number and new quarks carrying it, the absence of the pseudoscalar partners of the  $\psi$ and  $\psi'$ , reachable by gamma ray transitions from the  $\psi'$ , is a serious difficulty.

Thus, although a great deal of experimental progress has been made on the  $\psi$ 's in the past six months, the critical, unanswered questions remain as they were in January.<sup>58</sup> For any theory with a new quark and associated additive quantum number, the most pressing issue is <u>spectroscopic</u>. First, there should exist bound states consisting of one new quark and old quarks, and which therefore carry the new quantum number. We have every reason to believe that above ~4 GeV in electron-positron collisions, pairs of such particles should be present in a good fraction of the events, but none have been found. Second, additional new quark-new antiquark states should exist. The most unavoidable of these are the  ${}^{1}S_{0}$  pseudoscalar states which are the quark model partners of the  ${}^{3}S_{1} \psi$ 's. Again, experimental establishment of their existence has not been forthcoming.

Therefore, the complete implications of the discovery of the  $\psi$ 's still remain to be found. For the future, the only guarantee that we can make on the basis of theory is that further major experimental discoveries lie ahead.

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