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OBSERVATION OF THE DECAY $\psi(3684) \to \psi(3095)\eta$*

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ABSTRACT

We have observed the decay $\psi(3684) \to \psi(3095)\eta$ with a branching fraction of $4.3 \pm 0.8\%$. This measurement, together with previous measurements of $\psi(3684) \to \psi(3095)$ + anything, $\psi(3684) \to \psi(3095)\pi^+\pi^-$, and $\psi(3684) \to \psi(3095)\gamma\gamma$, indicates that isospin is conserved in the decay $\psi(3684) \to \psi(3095)\pi\pi$ and establishes the isospin and G-parity of the $\psi(3684)$ to be $I^G = 0^-$.

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Since the discovery of the $\psi(3684)$ ($\equiv\psi'$)[1], there has been speculation about its relationship to the $\psi(3095)$ ($\equiv\psi$).[2] Some models such as the charm model[3] assign the ψ' to a radial excitation of the ψ, in which case the observed quantum numbers of the two states should be identical. Indeed, we know that both states have spin 1, odd parity, and odd charge conjugation.[4,5] We also know that the ψ, in its decays, behaves as a state with zero isospin and odd G-parity.[6] The observation of the decays of the ψ' into ψ with a large branching ratio[7] suggests a close relationship between the ψ and ψ'. From this previous report we can easily calculate that

$$\frac{\Gamma(\psi' \to \psi + \text{neutrals})}{\Gamma(\psi' \to \psi\,\pi^+\pi^-)} = 0.78 \pm 0.10. \qquad (1)$$

If ψ' to ψ decays proceeded entirely via the reaction $\psi' \to \psi\pi\pi$ with the π-π in a state of definite isospin, the ratio would have the value 1/2, 0 or 2 for π-π isospin 0, 1, or 2, respectively.[8] Isospin zero is clearly preferred, yet if we assume isospin zero, the excess of the ratio over its predicted value suggests the presence of $\psi' \to \psi$ + neutrals other than $\psi' \to \psi\pi^0\pi^0$. The presence of $\psi' \to \psi\gamma\gamma$ [9,10] does not completely account for the excess. In this letter we show that the decay $\psi' \to \psi\eta$ accounts for the remaining excess, thus indicating the conservation of isospin in the decay $\psi' \to \psi\pi\pi$ and establishing the isospin of the ψ' to be $I^G = 0^-$.

The primary evidence for $\psi' \to \psi\eta$ comes from a study of the decay sequence,

$$\psi' \to \psi\eta, \quad \eta \to \pi^+\pi^-\pi^0 \text{ or } \pi^+\pi^-\gamma, \quad \psi \to \mu^+\mu^-,$$

where both muons and one or both of the charged pions are observed with the SLAC-LBL magnetic detector at the SLAC storage ring SPEAR.[11] Figure 1 shows the invariant mass distribution of the two oppositely charged particles of highest momenta for all three or four prong events. Muon masses have been assumed. Electron pairs have been eliminated by shower counter pulse height criteria. Events with dimuon mass squared between 8.8 and 10.4 $(\mathrm{GeV}/c^2)^2$ are selected as $\psi' \to \psi$ decays. Contamination from other processes is estimated to be less than 0.5%. After the elimination of electron-positron pairs from photon conversions (opening angles of less than ten degrees), tracks which intersect the aluminum support posts of the detector, and tracks which scatter in the beam pipe or surrounding material, there remain 1146 events from an initial sample of approximately 100,000 ψ' decays. About 60% of these 1146 events have only three prongs.

The mass of the muon pair is constrained to be equal to the ψ mass in order to improve the resolution. We then plot the square of the missing mass to the ψ and the pion in three prong events in Figure 2. The peak at 0.02 $(\mathrm{GeV}/c^2)^2$ is due to the reaction $\psi' \to \psi\pi^+\pi^-$. The solid curve is drawn by eye through the low mass side of the peak and reflected on the high side. Candidates for $\psi' \to \psi\eta$ are found primarily at higher missing mass as shown by a Monte Carlo prediction indicated by the dashed curve.

We select the 32 events for which the square of the missing mass in Fig. 2 is greater than 0.08 $(\mathrm{GeV}/c^2)^2$. To this sample we add the 16 four-prong events for which the square of the missing mass to the ψ and either pion is greater than 0.08 $(\mathrm{GeV}/c^2)^2$. The 1098 remaining events are considered to be $\psi' \to \psi\pi^+\pi^-$ decays. For the 48

event sample, we plot the square of the mass recoiling against the muon pair (m_x^2) in Fig. 3a. The events peak at the square of the η mass with an observed rms width of 0.02 $(\mathrm{GeV}/c^2)^2$ in good agreement with our experimental resolution. We thus identify these events as $\psi' \to \psi\eta$ decays. Figure 3b shows the m_x^2 spectrum for the 1098 $\psi' \to \psi\pi^+\pi^-$ decays.

Of the 48 $\psi' \to \psi\eta$ candidates, we expect from Fig. 2 that about four are contamination from multipion decays and $\psi' \to \psi\pi^+\pi^-$ decays. Also, about twelve true $\psi' \to \psi\eta$ events were incorrectly classified as $\psi' \to \psi\pi^+\pi^-$ decays. After making these corrections, and additional corrections for events lost due to scattering, photon conversions, and geometrical acceptance, we calculate the branching ratio

$$\frac{\Gamma(\psi' \to \psi\eta)}{\Gamma(\psi' \to \mathrm{all})} = 4.3 \pm 0.8\% \ . \qquad (2)$$

We will now assume that all $\psi' \to \psi$ decays other than $\psi' \to \psi\pi^+\pi^-$ $\psi' \to \psi\gamma\gamma$, and $\psi' \to \psi\eta$ are from the decay $\psi' \to \psi\pi^0\pi^0$. There are two justifications for this assumption: (a) The m_x^2 recoiling against the dimuon pair in $\psi' \to \psi$ + neutrals is consistent with this assumption (to be discussed below); (b) The frequency of shower counter firings in $\psi' \to \psi$ + neutrals is consistent with this assumption. In addition the DASP group has observed $\psi' \to \psi\pi^0\pi^0$ directly and has observed no $\psi' \to \psi$ modes other than those above.[12] We thus can convert out previous results, equation (1)[13] into

$$\frac{\Gamma(\psi' \to \psi\pi^0\pi^0)}{\Gamma(\psi' \to \psi\pi^+\pi^-)} = 0.53 \pm 0.06 \qquad (3)$$

by subtracting the $\psi' \to \psi\gamma\gamma$ and $\psi' \to \psi\eta$ decays. This result is in

excellent agreement with the expected value of 0.52 for a pure isospin zero $\pi\pi$ system.

This consistency strongly suggests that the decay $\psi' \to \psi\pi\pi$ conserves isospin. Since the ψ has zero isospin and negative G-parity,[6] the ψ' must then also have zero isospin and negative G-parity. The observation of $\psi' \to \psi\eta$ independently demonstrates that the ψ' has zero isospin.

As a final consistency check we will search for the decays

$$\psi' \to \psi\eta \quad \eta \to \text{neutrals}, \quad \psi \to \mu^+\mu^-.$$

We take events in which a muon pair within our mass cut is observed, but no other charged particles. For each event we calculate the square of the mass recoiling against the muon pair (m_x^2). Using Eq. 3 and the m_x^2 spectrum in Fig. 3b, we subtract the contribution from $\psi' \to \psi\pi^0\pi^0$ events and $\psi' \to \psi\pi^+\pi^-$ events in which both pions escaped detection. The result is shown in Fig. 3c. The peak at $m_x^2 = 0.3\ (\mathrm{GeV}/c^2)^2$ indicates the presence of about 200 $\psi' \to \psi\eta$ events where $\eta \to$ neutrals. From these data we obtain

$$\frac{\Gamma(\eta \to \text{charged modes})}{\Gamma(\eta \to \text{neutral modes})} = 0.37 \pm 0.10 \qquad (4)$$

in good agreement with the value of 0.406 ± 0.013 derived from a fit to the world data.[14]

The events in Fig. 3c not in the η peak are mostly $\psi' \to \psi\gamma\gamma$ events[10] plus some background from the radiative tail of $\psi' \to \mu^+\mu^-$. In particular, there is no peak at or near zero mass. We can place

the following 90% c.l. upper limit[15] on $\psi' \to \psi\pi^0$ and $\psi' \to \psi\gamma$:

$$\frac{\Gamma(\psi' \to \psi\pi^0) + \Gamma(\psi' \to \psi\gamma)}{\Gamma(\psi' \to \text{all})} < 0.15\% \qquad (5)$$

Isospin conservation and the assignment of I=0 to the ψ' provides the only known explanation for the absence of $\psi' \to \psi\pi^0$.

In conclusion, we have shown the existence of $\psi' \to \psi\eta$, with a branching ratio of $4.3 \pm 0.8\%$, and that the ψ' has zero isospin and negative G-parity. The decay $\psi' \to \psi\eta$ is suppressed by SU3 if the ψ and ψ' are both SU3 singlets, as predicted in the charm model. It has limited phase space since the available kinetic energy is only 40 MeV. To conserve parity it must be a P-wave decay; thus there is an additional angular momentum barrier suppression. In light of these considerations, it is surprising to us that the $\psi' \to \psi\eta$ branching ratio is as large as it is.

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to available phase space, the predictions become 0.524 for isospin 0 and 2.10 for isospin 2.

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13. Our result (1) was obtained assuming the angular distribution of the muons in $\psi' \to \psi + \text{neutrals}$ ($\psi \to \mu^+\mu^-$) is $1 + \cos^2\theta$. For $\psi' \to \psi\eta$, the true distribution is $5-3\cos^2\theta$, while for $\psi' \to \psi\gamma\gamma$ we have assumed the muons are isotropic. The corrected ratio is 0.73 ± 0.09.
14. Particle Data Group, Phys. Lett. 50B, April 1974.
15. This upper limit was calculated before the $\psi' \to \psi\pi^0\pi^0$ subtraction, and thus does not depend on the $\pi\pi$ isospin assumption.

Figure Captions

1. The square of the $\mu^+\mu^-$ effective mass for the highest momentum oppositely charged particle pairs from each 3 or 4 prong event, with e^+e^- pairs excluded.
2. The square of the missing mass in $\psi' \to \psi + \pi + X$ ($\psi \to \mu^+\mu^-$) for three prong events. The curves are explained in the text.
3. Square of the recoil mass to the muon pair for:
   (a) $\psi' \to \psi\eta$ candidates with $\eta \to$ charged modes
   (b) $\psi' \to \psi\pi^+\pi^-$ events
   (c) $\psi' \to \psi$ + neutrals, with $\psi' \to \psi\pi\pi$ subtracted

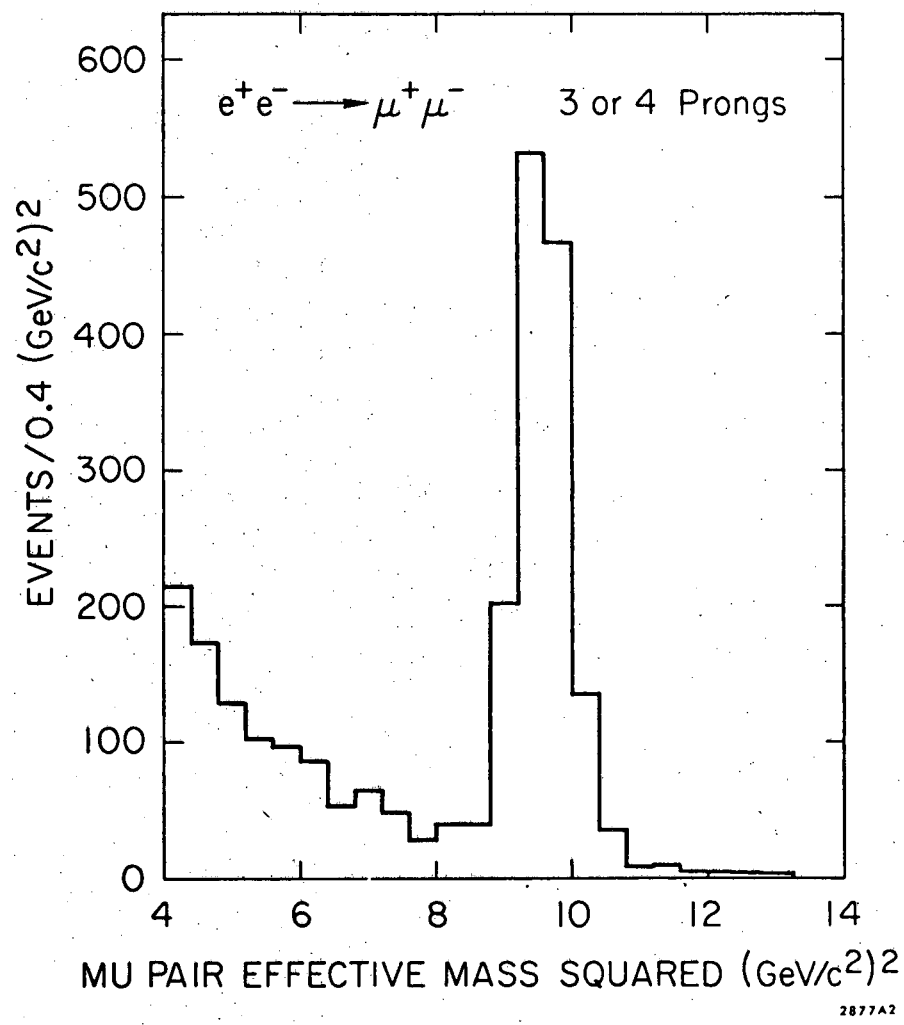

Fig. 1

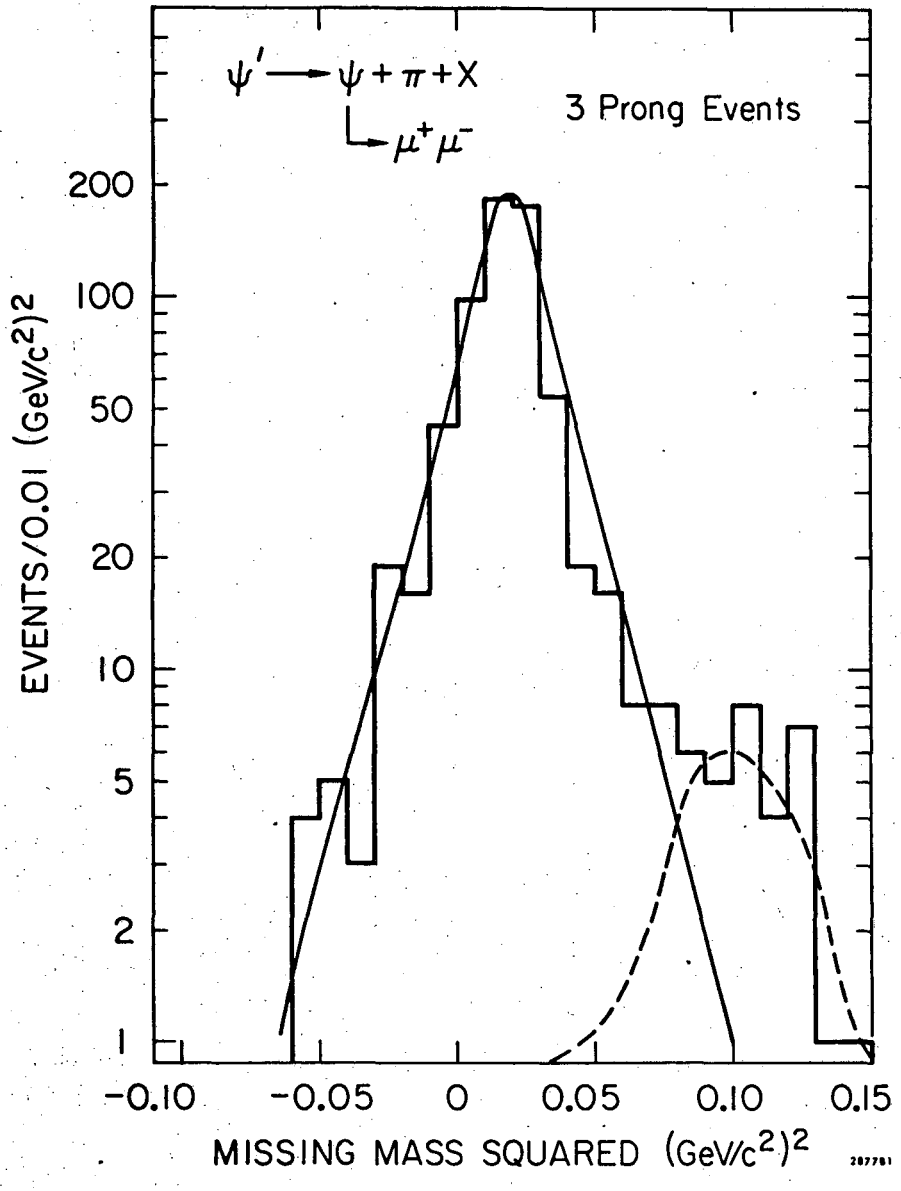
ψ' → ψ + π + X
└→ μ⁺μ⁻
3 Prong Events
EVENTS/0.01 (GeV/c²)²
200
100
50
20
10
5
2
1
-0.10
-0.05
0
0.05
0.10
0.15
MISSING MASS SQUARED (GeV/c²)²

Fig. 2

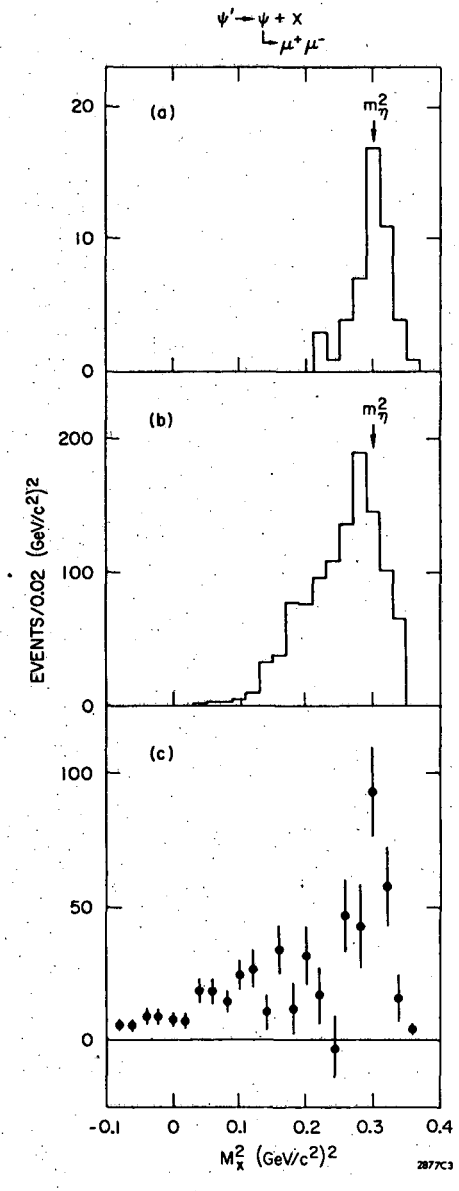
ψ' → ψ + X
└→ μ⁺μ⁻
(a)
(b)
(c)
m²η
EVENTS/0.02 (GeV/c²)²
20
10
0
200
100
0
100
50
0
-0.1
0
0.1
0.2
0.3
0.4
M²X (GeV/c²)²

Fig. 3

0 0 0 0 4 5 0 0 2 2 0

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