[6]Many of our conclusions follow from features of $D(z)$ that are expected to be quite general. Such results should have a qualitative validity even if C is a baryon.

[7]S. J. Barish *et al.*, ANL Report No. ANL-HEP-CP-75-39 (unpublished); B. P. Roe, in Proceedings of the Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975 (to be published).

[8]A z^{-1} behavior implies logarithmically growing multiplicity with energy. In the dimuon events under consideration, however, the multiplicity of C (neglecting associated production) is one per event. A realistic form for $D(z)$ should behave more smoothly at small z.

[9]Most of the dimuon characteristics in our model depend only weakly on the details of the decay mechanism.

[10]The decaying hadron C can carry a "natural" transverse momentum associated with the production process. This momentum will be of order 300–400 MeV if the transverse characteristics of C are similar to those of ordinary current fragments, but could conceivably be higher. A transverse momentum of order 200 MeV can also arise from the Fermi motion of the nucleon in the target nucleus. The cumulative effect of these corrections will be to smear the $k_\perp$ distribution of the secondary muon so that the observed $k_\perp$ cutoff exceeds $M_C/2$. The empirical distribution shown in Fig. 2 can thus be consistent with a charmed-particle mass as low as 2 GeV.

[11]We have examined possible modifications of our asymptotic results arising from finite neutrino energies and the nonvanishing mass of C (L. M. Sehgal and P. M. Zerwas, to be published). For the E_+/E_- distribution shown in Fig. 2(a), these corrections are found to be of relative order $(M_C/E_\nu)/(E_+/E_-)$. These corrections are significant only at very small values of E_+/E_-, and tend to improve the agreement with the data in that region.

[12]A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1249 (1975).

[13]Sehgal and Zerwas, Ref. 11.

Observation of the Decay $\psi(3684)\to\psi(3095)\eta$†

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We have observed the decay $\psi(3684)\to\psi(3095)\eta$ with a branching fraction of $(4.3\pm0.8)\%$. This measurement, together with previous measurements of $\psi(3684)\to\psi(3095)+\text{anything}$, $\psi(3684)\to\psi(3095)\pi^+\pi^-$, 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 $I^G=0^-$.

Since the discovery of the $\psi(3684)$ (ψ'),[1] there has been speculation about its relationship to the $\psi(3095)$ (ψ).[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

$$\frac{\Gamma(\psi'\to\psi+\text{neutrals})}{\Gamma(\psi'\to\psi\pi^+\pi^-)}=0.78\pm0.10\,. \qquad (1)$$

If ψ' decays to ψ 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 $\frac{1}{2}$, 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 $\psi'\to\psi+\text{neutrals}$ 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 and G parity of the ψ' to be $I^G=0^-$.

The primary evidence for $\psi'\to\psi\eta$ comes from a

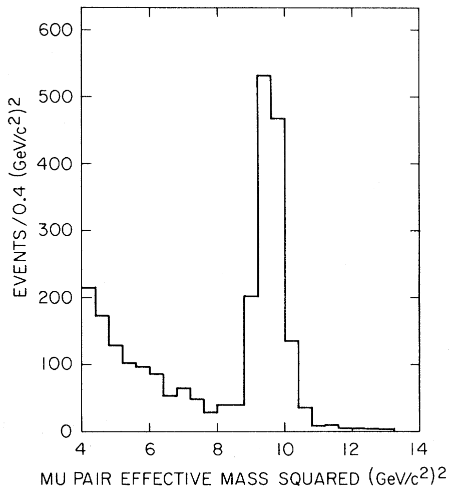

FIG. 1. The square of the $\mu^+\mu^-$ effective mass for the highest-momentum, oppositely charged particle pairs from each three- or four-prong event, with e^+e^- pairs excluded.

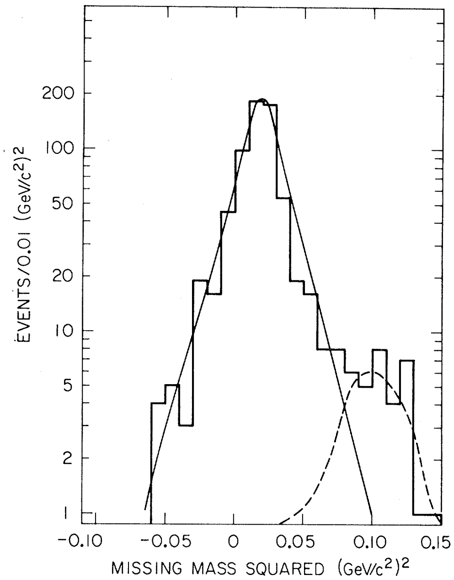

FIG. 2. The square of the missing mass in $\psi' \to \psi + \pi + X$ ($\psi \to \mu^+\mu^-$) for three-prong events. The curves are explained in the text.

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 Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at the Stanford Linear Accelerator Center 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 the square of the dimuon mass between 8.8 and 10.4 $(\text{GeV}/c^2)^2$ 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 10 deg), 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 Fig. 2. The peak at 0.02 $(\text{GeV}/c^2)^2$ 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 onto 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 $(\text{GeV}/c^2)^2$. To this sample we add the sixteen four-prong events for which the square of the missing mass to the ψ and either pion is greater than 0.08 $(\text{GeV}/c^2)^2$. 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. 3(a). The events peak at the square of the η mass with an observed rms width of 0.02 $(\text{GeV}/c^2)^2$ in good agreement with our experimental resolution. We thus identify these events as $\psi' \to \psi\eta$ decays. Figure 3(b) 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,

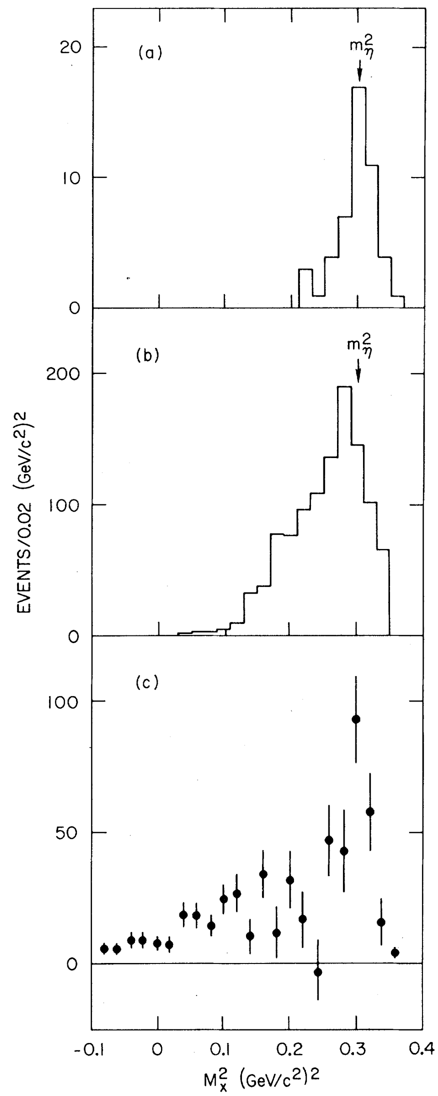

FIG. 3. Square of the recoil mass to the muon pair for (a) $\psi' \to \psi\eta$ candidates with $\eta \to$ charged modes; (b) $\psi' \to \psi\pi^+\pi^-$ events; (c) $\psi' \to \psi$+neutrals, with $\psi' \to \psi\pi\pi$ subtracted.

and geometrical acceptance, we calculate the branching ratio

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

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 double-arm-spectrometer 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 our previous results, Eq. (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-0 π-π 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. 3(b), 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. 3(c). The peak at $m_X^2 = 0.3$ (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. 3(c) 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%-confidence 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 SU(3) if the ψ and ψ' are both SU(3) 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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[1]G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[3]T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975).

[4]A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975).

[5]V. Lüth *et al.*, Phys. Rev. Lett. 35, 1124 (1975).

[6]B. Jean-Marie *et al.*, Phys. Rev. Lett. 36, 291 (1976).

[7]G. S. Abrams *et al.*, Phys. Rev. Lett. 34, 1181 (1975).

[8]The mass differences between $\pi^{\pm}$ and π^0 modify these predictions slightly. If the expected rates are taken as just proportional to available phase space, the predictions become 0.524 for isospin 0 and 2.10 for isospin 2.

[9]W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975).

[10]W. Tanenbaum *et al.*, Phys. Rev. Lett. 35, 1323 (1975).

[11]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[12]B. H. Wiik, DESY Report No. DESY 75/37 (unpublished).

[13]Our result (1) was obtained by assuming that the angular distribution of the muons in

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

is $1+\cos^2\theta$. For $\psi' \to \psi\eta$, the true distribution is $5-3\times\cos^2\theta$, while for $\psi' \to \psi\gamma\gamma$ we have assumed that the muons are isotropic. The corrected ratio is 0.73 ± 0.09.

[14]V. Chaloupka *et al.*, Phys. Lett. 50B, 1 (1974).

[15]This upper limit was calculated before the $\psi' \to \psi\pi^0\pi^0$ subtraction, and thus does not depend on the π-π isospin assumption.

Oscillations in the Excitation Function for Complete Fusion of $^{16}O + ^{12}C$†

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The total fusion cross section for the $^{16}O + ^{12}C$ system has been measured in the ranges 13 MeV $\leq E_{c.m.} \leq$ 27 MeV. The cross section is found to increase with bombarding energy up to $E_{c.m.} \approx$ 17 MeV but to stay roughly constant at higher energies, in qualitative agreement with predictions of current models. Superimposed on this average cross-section behavior we observe unexpected oscillations with a period of about 3–4 MeV (c.m. energy).

Fusion cross sections in reactions induced by heavy ions have been measured in recent years for a variety of projectiles, targets, and bombarding energies.[1-3] In reactions between light- and medium-weight nuclei, fusion processes have been found to account for most of the total reaction cross section (σ_{reac}) at energies not too far above the Coulomb barrier.[1,2] In these systems at much higher bombarding energies, however, the fusion cross section (σ_{fus}) constitutes a significantly smaller fraction of σ_{reac}.[3] The energy dependence of σ_{fus} is qualitatively explained by semiclassical models which assume that fusion occurs whenever the projectile and target nuclei reach a certain critical separation.[4-6] However, fusion measurements have not been made over a sufficiently wide energy and mass range to test stringently the predictions of these models. In the present Letter we report measurements of σ_{fus} for the light-mass system $^{16}O + ^{12}C$ at bombarding energies spanning the region where σ_{fus} is predicted to begin to deviate significantly from σ_{reac}. Superimposed on an average energy dependence consistent with calculations of Glas and